THE EFFECTS OF CLIMATE CHANGE ON THE RADIAL GROWTH OF FOUR SHELTERBELT SPECIES ACROSS THE BROWN, DARK BROWN, AND BLACK SOIL ZONES OF SASKATCHEWAN

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ABSTRACT

Mitigating climate change has become a common theme in numerous research projects in Saskatchewan, and shelterbelts are highlighted as one of the potential ways to help mitigate climate change by sequestering carbon. The issue with shelterbelts, is that it is unknown how shelterbelts will grow under future climate change conditions in the already harsh climate of the Saskatchewan prairies. The purpose of this study was to predict the radial growth of the shelterbelt species green ash (*Fraxinus pennsylvanica*), hybrid poplar (*Populus* hybrids), Scots pine (*Pinus sylvestris*), and white spruce (*Picea glauca*) across the Brown, Dark Brown, and Black soil zones of Saskatchewan.

Tree cores were collected at 68 sites for this study, and for each site a master chronology of tree rings was constructed. The master chronologies and past climate records were used in a linear regression model to determine the past responses of the tree species at each site to climate. These responses along with future climate data from climate models were used to predict the future growth of each species at each site. Maps summarizing the predicted growth of each species were created to make the information easier to interpret.

Green ash growth is predicted to increase across most of south-central Saskatchewan up to the year 2100, excluding areas in the more westerly areas of the province. The reason for this increase is mainly attributed to green ash's positive relationship to spring and June precipitation, which is predicted to increase in the future. Hybrid poplar radial growth is predicted to slightly decrease in the future. This decrease is small and will be slow to develop because the decreases in hybrid poplar radial growth that are caused by rising summer temperatures are counteracted by predicted increases in autumn precipitation which is positively related to hybrid poplar growth the following year. Scots pine's driver of growth is spring and summer (mainly June) precipitation which is predicted to increase under climate models. For this reason, Scots pine growth is predicted to increase in the westerly areas of southern Saskatchewan. Scots pine growth is also predicted to increase in the north, which is attributed to the positive impact that spring temperature has on Scots pine growth. White spruce radial growth is predicted to decrease across the Brown, Dark Brown, and Black soil zones of Saskatchewan because rising future temperatures will likely cause temperature-induced drought in white spruce across the southern half of Saskatchewan. Predicting the growth of these common shelterbelt species will help

landowners choose a shelterbelt species that will grow well in their area of the province under climate change conditions and may help policy makers to make informed decisions about using shelterbelts for potential carbon offset credits.

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DEDICATION

To my mom Lisa and my dad Jeff.

Thank you for your love and encouragement

And always believing in me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

PFRA	Prairie Farm Rehabilitation Administration
OM	Organic matter
GCMs	Global Climate Models
CMIP5	Couple Model Intercomparison Project Phase 5
KKZ	Katsavounidis-Kuo-Zhang
ACCESS1-0	Australian Community Climate and Earth Simulator version 1
BOM	Bureau of Meterology
CSIRO	Commonwealth Scientific and Industrial Research Organization
MET office	Meteorological office
NOAA	National Oceanic and Atmospheric Administration
CanESM2	Canadian Earth System Model second generation
CNRM-CM5	Fifth model developed by Centre National de Recherches Météorologiques
INMCM4	Phase 4 of the Institute of Numerical Mathematics Climate Model
SAT	Surface air temperature
IPCC	Intergovernmental Panel on Climate Change
RCPs	Representative Concentration Pathways
CO2	Carbon Dioxide
EPIC	Erosion Productivity Impact Calculator
AGGP	Agriculture and Greenhouse Gases Project
3PG model	Physiological Processes Predicting Growth model
CBM-CFS3	Carbon budget model of the Canadian Forest Sector
MSI	Mean Series Intercorrelation
PCIC	Pacific Climate Impacts Consortium

AIC	Aikaike's Information Criterion
VIF	Variance Inflation Factor
MAM	March, April, May
JJA	June, July, August
SON	September, October, November
DJF	December, January, February
AMS	Average Mean Sensitivity

1 INTRODUCTION

1.1 General introduction

Shelterbelts are defined as a row of planted trees or shrubs that are designed to protect a field from soil erosion and/or wind damage. They have been a key farm management practice since producers began settling on the Saskatchewan prairies in the early 20th century and are commonly found in both farmyards and fields. Research has revealed that shelterbelts provide many more benefits than what they were originally intended for. In fact, economic studies have estimated producer and public benefits of Saskatchewan shelterbelts at $140 million from 1981 to 2001 (Kulshreshtha and Kort, 2009). Shelterbelt benefits for producers include increased crop yield, quality, and livestock weight gain, and decreased livestock stress and mortalities; all of which contribute to greater farm revenue (Kulshreshtha and Kort, 2009; Rempel, 2014). The public benefits from shelterbelts include improved air and water quality, reduced traffic accidents due to decreased snow and soil drifting, and increased aesthetics and biodiversity; all of which contribute to enhanced human health and quality of life (Kulshreshtha and Kort, 2009; Rempel, 2014).

Despite the numerous benefits associated with shelterbelts, an audit by Agriculture and Agri-Food Canada (2004) found that the rationale of the shelterbelts program was outdated, partly because new farming practices like conservation tillage, reduce soil erosion and hence reduce the need for shelterbelts. These findings lead to the shutdown of the Shelterbelt Centre at Indian Head, Saskatchewan in 2013. Many landowners also agree with this concept that shelterbelts are no longer needed, because conservation tillage practices negate the need for shelterbelt protection from soil erosion, and more space is needed for increasingly larger equipment (Rempel, 2014). In response to this concept, shelterbelts are being removed at a startling rate. Yet, in dry conditions conservation tillage practices are often not enough to slow the rate of soil erosion. Shelterbelts are still relevant today and can help provide solutions to many problems that society faces today. Climate change, along with a multitude of issues stemming from an exponentially increasing human population and increased atmospheric pollution from fossil fuel energy generation, plague our society, but shelterbelts can help mitigate some of these related issues. Shelterbelts improve water quality, which has become an issue of growing concern in recent years due to increased agricultural pollution in waterways and its resulting harmful biological effects on animal and human health (Ryszkowski and Kedziora, 2007; Trevino-Garrison et al., 2015). They help to mitigate climate change by sequestering carbon, and shelterbelts reduce pesticide drift, which is currently an issue for many producers who are practicing conservation till, because they rely more heavily upon herbicides to control their weeds (Schiffman, 1998; Tyndall and Colletti, 2000; Kulshreshtha and Kort, 2009; Amichev et al., 2016a). The audit by Agriculture and Agri-Food Canada (2004) mistakenly concluded that shelterbelt implementation is outdated, because shelterbelts align with current conservation tillage practices by reducing pesticide drift and helping to mitigate climate change by sequestering carbon.

Shelterbelt research had become increasingly popular in recent years because of the looming threat of climate change. The ability of shelterbelts to sequester large amounts of carbon, and potentially buffer the negative effects of climate change on farms, accounts for its increasing popularity (Parry and Carter, 1989; Parry et al., 2004; Wall and Smit, 2005; Kulshreshtha and Kort, 2009; Rempel, 2014; Amichev et al., 2016b). Producers face major challenges related to climate change in the form of predicted increased aridity, increased intensity and frequency of extreme weather events, and increased pest and disease infestations (Parry and Carter, 1989; Parry et al., 2004; Wall and Smit, 2005). In response to these potential issues, shelterbelts have been named as a tool to reduce the negative effects related to climate change, by reducing wind speeds and maintaining water tables and soil moisture (Wall and Smit, 2005). However, the effects of climate change on shelterbelt growth is unknown, and until it is determined, a shelterbelts ability to sequester carbon, mitigate climate change, and help buffer the negative effects of climate change in the future is in question..

1.2 Rationale and objectives of research

Many producers are unaware of the numerous benefits that shelterbelts can provide, and if they are aware, often do not associate these benefits with direct economic gain (Rempel, 2014). Similar to every business, economics is the driving factor controlling whether a practice is implemented or not. Currently, shelterbelts are being removed at an increasing rate, partly because the economic benefits of shelterbelts are not seen in a quantifiable amount to most producers (Rempel, 2014; Ha et al., 2019). However, if carbon pricing is implemented in

Saskatchewan, the economic potential of shelterbelts will likely be realized by producers, and more shelterbelts will be planted for economic gain (Kulshreshtha and Kort, 2009; Rempel, 2014). In the instance of carbon pricing, it will be essential to know how much carbon will be sequestered by shelterbelts. The problem is, we do not know how climate change will affect future shelterbelt growth and its corresponding carbon sequestration. In response to this problem, the first objective of my research was to use dendrochronology techniques to study the past growth of green ash (*Fraxinus pennsylvanica*), hybrid poplar (*Populus* hybrids), Scots pine (*Pinus sylvestris*), and white spruce (*Picea glauca)* in the Brown, Dark Brown, and Black soil zones of Saskatchewan and determine what climate variables most influence radial growth for each species. Since many sites were collected across Saskatchewan, the spatial pattern of where certain climate variables most influence growth of each species was also examined. The second objective was to use the past growth responses to climate for each shelterbelt species to predict future-radial growth. The logic behind this was that the relationship between past climate and tree- ring width could be used in a linear regression equation with future climate models (predicts future precipitation and temperature) to predict how each shelterbelt species will grow in the future (Laroque, 2002; Phillips and Laroque, 2008; Speer, 2012). My results will allow me to determine what species will be best adapted to the different regions across southern Saskatchewan, and in turn, I will be able to recommend to landowners which tree species will succeed in their area, which may help optimize carbon sequestration of shelterbelts.

1.3 Organization of thesis

The format of this thesis is organized in a traditional style. Chapter one and two are the Introduction and Literature Review respectively, which explain general shelterbelt and climate change concepts, along with introducing climate modelling and exploring similar studies to this research. Following Chapter 1 and 2 is the Materials and Methods (Chapter 3), and Chapter 4 is the Results section which addresses objectives one and two. The Discussion (Chapter 5) explains the reasoning behind the changes in each shelterbelt species' growth. Chapter 6 provides a Synthesis of the research in this thesis and concludes the main takeaways. Chapter 7 is the References followed by an Appendices.

2 LITERATURE REVIEW

2.1 Saskatchewan soil zones

Saskatchewan is located amidst the rain shadow from the Canadian Rockies, which greatly influences the climate and vegetation in the province. The rain shadow has the most influence on the southwestern portion of the province, resulting in increasing moisture availability from southwest to northeast Saskatchewan (Fuller, 2010; Shorthouse, 2010). This moisture gradient, and the climatic and vegetative variations across the Prairie Provinces, helped form the five soil zones in Saskatchewan. These soil zones include the Brown, Dark Brown, Black, Gray, and Dark Gray soil zones (Figure 2.1), which approximately correspond to the mixed grassland, moist mixed grassland, aspen parkland, and boreal forest ecoregions (boreal transition, mid-boreal upland, mid-boreal lowland) respectively (Fuller, 2010). The Dark Gray and Gray soil zones are not included in my study because they are located in the boreal forest ecoregions where trees naturally occur in abundance, and shelterbelts here are generally characterized in agricultural areas as leftover strips of natural forest. Consequently, few landowners from the Gray and Dark Gray soil zones obtained free seedlings from the Prairie Farm Rehabilitation Administration (PFRA) (Piwowar, Amichev, and Van Rees Rees, 2017), making this study less relevant to the Gray soil zones.

The Brown soil zone is located in southwestern Saskatchewan (Figure 2.1). The zone approximately corresponds with the mixed grassland ecoregion, and is characterized by Brown Chernozemic soils (Fuller, 2010; Shorthouse, 2010). The mixed grassland ecoregion typically experiences an annual summer temperature of 16˚C and winter temperature of -10˚C, along with an average annual precipitation of 250-350 mm (Shorthouse, 2010). Moisture deficits are common in this area because of low precipitation, high temperatures in the summers, and the large numbers of chinooks that pass through and sublimate snow (Shorthouse, 2010). Plants in the Brown soil zone are limited by moisture, so plant productivity and organic matter (OM) in the soil are lower than the other soil zones, which explains the characteristic brown colour of the soil. Drought and high winds are the typical risks that agricultural producers experience in this area.

The Dark Brown soil zone is associated with the moist mixed grassland ecoregion (Fuller, 2010). The moist mixed grassland differs from the mixed grassland because it is typically more productive and produces greater biomass. The Dark Brown soil zone's annual average summer and winter temperatures are 0.5˚C and 1˚C cooler than the Brown soil zone, and their mean annual precipitation ranges from 350-450 mm, which is a 0-200 mm increase in precipitation from the Brown soil zone (Shorthouse, 2010). The presence of more moisture and less evaporation in this area allows for greater plant production, higher OM, and darker, more nutrient rich soils. This area is somewhat less prone to drought and high winds than the Brown soil zone, but it is still a serious concern for agricultural producers in the area.

The aspen parkland ecoregion is associated with the Black soil zone and represents the transitional area from the grasslands to the south and the boreal forest to the north (Fuller, 2010). In its native state, the aspen parkland region is characterized by northern and plains rough fescues or moist mixed grass prairie that is interspersed with copses of trembling aspen. The area experiences long-cold winters, and short-cool summers, and has a mean annual precipitation of 350-450 mm. In general, the Black soil zone has higher precipitation and lower average temperatures than the Brown and Dark Brown soil zones, which explains the higher productivity, increased OM, and darker soil in the area (Shorthouse, 2010). Agricultural producers in the Black soil zone often have issues with late frosts in the spring and early frosts in the fall because of their shorter growing season. As you move north and east along the moisture gradient in Saskatchewan, the soil OM and productivity of the land increases, and the soil becomes darker in colour.

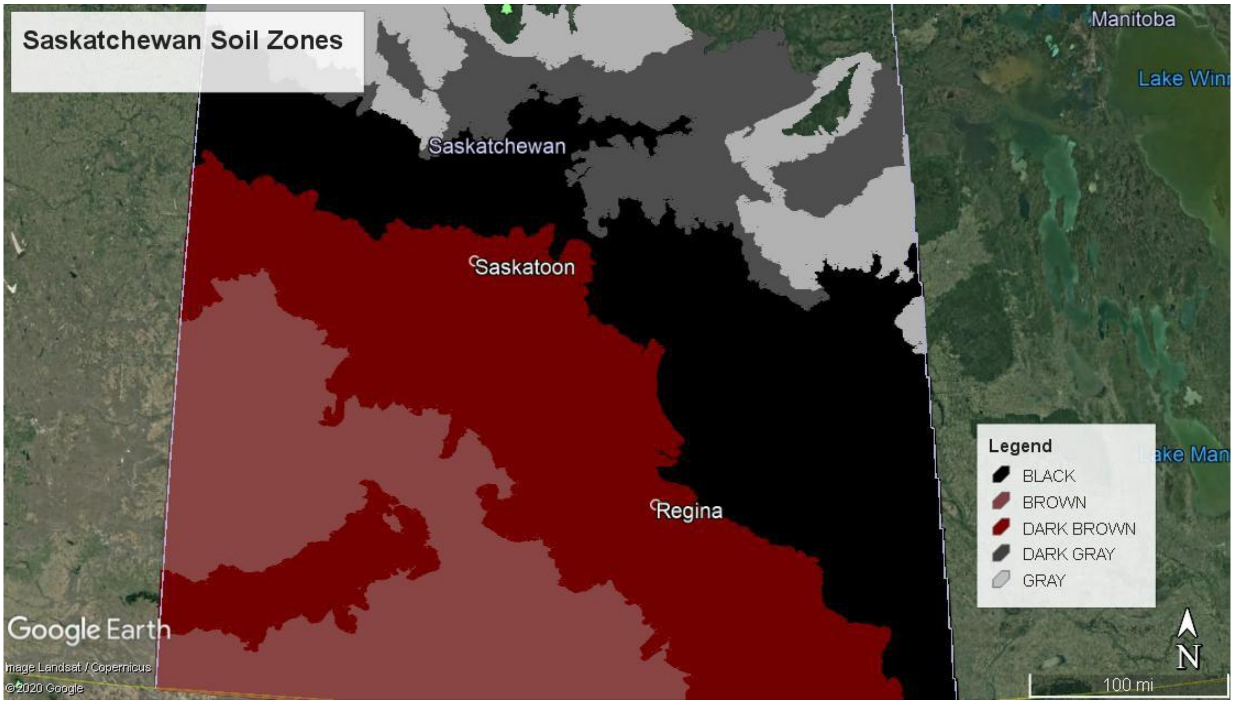

Figure 2.1 The five soil zones in Saskatchewan – Gray, Dark Gray, Black, Dark Brown, and Brown soil zones. Map data 2020 Google.

2.2 The history of settlement on the prairies

The leader of the British North American Exploring Expedition, Captain John Palliser, surveyed Western Canada in 1859 in the midst of a ten-year drought on the prairies (Marchildon et al., 2008, 2009). Captain Palliser named an area of the prairies the Palliser triangle because of its aridity and deemed the area unsuitable for agriculture. The Palliser triangle is situated mainly in the Brown soil zone of the prairies and covers 200,000 km^2 of Southern Alberta and Saskatchewan, and a small section of southern Manitoba (Marchildon et al., 2008, 2009). Despite Palliser's findings that the area suffered from reoccurring drought, these parts of the prairies were opened for settlement in the late 19th century (Baker, 1928; Dale-Burnett, 2002; Marchildon et al., 2008, 2009).

The pervasive eolian erosion problems and dust storms common in the early 20th century were mainly caused by the standard farming practices at the time given by agricultural experts, which promoted intensive tillage. In addition, bumper crops and good grain prices in the early years of settlement encouraged agricultural settlement into marginal areas, where the soil was particularly sensitive to drought and erosion (Dunlop, 2000). These problems, along with increased mechanization and tractor usage on farms in the early-mid 1920's, promoted excessive tillage and caused massive soil erosion. The drought of the 1930's further exacerbated soil erosion, and when coupled with the economic collapse and crash of the grain prices in the 1930's, caused major financial hardships for prairie producers (Dyck, 2005). In response to this ecological and economic disaster, the government stepped in and formed the PFRA, an organization that gave free seedlings to landowners in the Prairie Provinces (Agriculture Canada, 1986, 2004). The purpose of the PFRA was to reduce family farm hardships by reducing soil erosion and conserving soil.

2.3 The history of shelterbelts in Saskatchewan

The Indian Head experimental farm in Saskatchewan was founded in 1888, and in 1890, a man named George Lang was hired to plant trees as windbreaks and research their benefits on the prairies (Agriculture Canada, 1986). Lang found that windbreaks increased the yields of crops, gardens, and fruit trees, by protecting them from wind damage.

These findings helped form the forest nursery station at Indian head in 1901, where they researched, grew, and distributed free trees to landowners. Their research involved collecting seeds from cold countries and growing them to determine if they were suitable for Saskatchewan climates (Agriculture Canada, 1986). The nursery also provided valuable information to landowners through their research, about how to plant and care for shelterbelts, what tree species to plant, and optimal shelterbelt designs.

During the drought of the 1930's, the PFRA and the forest nursery at Indian Head joined forces to plant over 2,000 km of shelterbelts on the prairies, to demonstrate their usefulness in reducing soil erosion (Agriculture Canada, 1986, 2004). In 1963, the shelterbelt program at Indian Head became part of the PFRA, and by 2009 over 600 million seedlings had been given to landowners across the prairies (Rempel, 2014). However, in 2013 the shelterbelt program was shut down by federal government cuts (Briere, 2012).

2.4 Producer benefits from shelterbelts

A study by Kort (1988) determined that shelterbelt induced increases in crop yields were the greatest in continental climates where crops are subjected to high winds, low moisture, or large changes in temperature. For example, areas that are subject to high winds are more susceptible to crop lodging, which is a form of wind damage that reduces crop yields and quality (Boldes et al., 2002). Shelterbelts have been proven to decrease lodging by reducing wind speed and trapping soil particles (Kort, 1988; Boldes et al., 2002). In moisture limited areas, snow trapping by shelterbelts, along with reduced evaporation and increased crop water-use efficiency that is characteristic of sheltered plants, have been proven to increase crop yields (Baldwin, 1988; Dickey, 1988; Kort, 1988; Norton, 1988). Therefore, well-designed shelterbelts have the potential to benefit crops and Saskatchewan producers.

Shelterbelts provide an improved microclimate that enhances growing conditions. Shelterbelt microclimates increase soil moisture and humidity and decrease evaporation and nighttime temperatures (Rosenburg et al, 1974; Kort 1988). This improved microclimate also enhances insect habitat and increases pollinator populations (Kort, 1988; Hill and Webster, 1995). Pollinators become stressed and have difficulty flying in windy areas, but shelterbelts help protect them from high wind speeds, which allows them to pollinate and contribute to greater crop yields (Hill and Webster, 1995).

Pesticides have become more predominant in recent years because of the switch to conservation tillage practices, which are more dependent upon pesticides (Hinkle, 1983). In response to this increased dependence, there has been growing concern about pesticide effects on waterways, beneficial insects, and neighboring crops. Several studies have researched ways to reduce these potential impacts, and have named shelterbelts as a key mitigation strategy to combat pesticide drift, because of their ability to reduce wind speeds and intercept airborne pesticides (Lazzaro et al., 2008; Ucar and Hall, 2001).

Shelterbelts protect livestock from cold winter winds and storms, and shade them in hot summers, thereby improving animal health, feeding efficiency, and reducing weather related deaths (Government of Canada, 2014; Gregory, 1995). Several studies in a review by Gregory (1995), suggested that shelterbelts enhance livestock growth and weight gain by reducing both physical and mental stress, especially during the winter in North America. The review also provided a few anecdotal reports from producers, stating that shelterbelts improve livestock water-use efficiency and forage productivity. Consequently, livestock producers who input well-designed shelterbelts can save money due to decreased mortalities and reduced water and feed requirements.

Shelterbelts can increase crop yields and quality, and increase livestock weight gain and feeding efficiency, which increases farm revenue (Kort, 1988; Gregory, 1995; Government of Canada, 2014). Producers gamble every year when they plant crops and forage, but shelterbelts can help reduce the negative effects of inclement weather and add stability to their operation. The benefits listed in this section provide rationale that shelterbelts align with current farming practices and goals and are still beneficial to producers today.

2.5 Public benefits from shelterbelts

The growing human population has encouraged the growth of the energy sector and more intensive agricultural operations, which has major implications on air quality and human health. Recent air quality issues due to increasing intensive livestock operations, has increased odor complaints and their associated health effects such as nose, throat, and eye irritations, and headaches and drowsiness (Schiffman, 1998). Shelterbelts can help mitigate this issue, by dispersing and reducing odours (Tyndall and Colletti, 2000; Kulshreshtha and Kort, 2009). Shelterbelts also improve the air quality by reducing fugitive dust particles and pesticide drift, both of which have been linked to cancers, bronchitis, lung issues, and even death (Kulshreshtha and Kort, 2009; Alewu, 2016). Poor air quality has been partly attributed to fossil fuel energy generation, which produces greenhouse gases, reduces air quality, and contributes to climate change. Shelterbelts have recently been recognized as an important tool to help mitigate climate change because of their ability to sequester large amounts of carbon. In southern Saskatchewan, white spruce alone are estimated to store 21.3 million tonnes of carbon (Amichev et al., 2020).Shelterbelts enhance surface and ground-water quality by slowing water runoff, and filtering pollutants such as soil sediments, fertilizers, manure, and pesticides (Ryszkowski and Kedziora, 2007; Kulshreshtha and Kort, 2009). Consequently, shelterbelts reduce water pollutants and protect drinking water. A review by Ryszkowski and Kedziora (2007) found that established shelterbelts reduce nitrates from fertilizer runoff in groundwater from 94.9-97.7 %. Excessive nitrates from fertilizers and human and animal waste, can cause eutrophication and algal blooms, and in some cases these algal blooms can produce powerful toxins that adversely affect human and animal health (Trevino-Garrison et al., 2015). Therefore, protecting waterbodies using mitigation strategies such as shelterbelts is in society's best interest.Reduced visibility from snow and soil drifting is common in Saskatchewan and is the cause of many traffic accidents. Shelterbelts have been shown to reduce traffic accidents by trapping snow and soil, and hence increasing visibility (Kulshreshtha and Kort, 2009).

The intrinsic value of nature is linked with its ability to provide habitat to wildlife and enhance and protect biodiversity. Shelterbelts are key elements of nature that provide corridors, shelter, and food for wildlife in agricultural settings, and ultimately help to increase biodiversity (Kulshreshtha and Kort, 2009). People can enjoy the benefits of enhanced biodiversity in the form of birdwatching, hunting, or simply appreciating its aesthetics. In fact, people who move to areas with more green spaces have been found to have an improved mental and in general tended to be happier (Alcock et al., 2014).

Shelterbelts provide many benefits to the public, many of which pertain to important issues that society faces today. For example, shelterbelts have been named a strategy to mitigate climate change, water pollution and eutrophication, pesticide drift, and traffic accidents. These benefits provide further evidence to support the relevance of shelterbelt implementation in Saskatchewan.

2.6 The science of climate change

The climate system involves complex interactions between the earth's atmosphere, land, hydrosphere, cryosphere, and biosphere (Bush and Lemmen, 2019). These interactions are driven by the amount of energy received by the sun; how much is reflected back into space and how much is absorbed by the ocean and land and re-emitted into the atmosphere. Once re-emitted, some of this energy makes its way through the atmosphere and is lost to space, but other energy is absorbed by the lower atmosphere and re-emitted again to heat the earth in a process called the greenhouse effect (Government of Canada, 2015; Bush and Lemmen, 2019). This balance of incoming and outgoing energy determines the Earth's average temperature, and any change in this balance changes the overall global average energy.

The substances that absorb energy in the lower atmosphere are called greenhouse gases and consist of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, water vapour and clouds (Bush and Lemmen, 2019). Water vapour concentrations are controlled by temperature; when it is warmer the air can hold more vapour. CO_2 is the most abundant greenhouse gas, is available at a wide range of temperatures and is responsible for controlling the temperature, which in turn controls the amount of water vapour the air can hold. The more CO_2 there is in the lower atmosphere, the warmer it is, and the more water vapour the air can hold (Riebeek, 2011). This increased moisture availability has slightly increased precipitation trends across Canada and has likely increased instances of extreme precipitation events (Bush and Lemmen, 2019). However, the effects of increasing greenhouse gases on the hydrological cycle is complex and very difficult to predict.

Human activities are producing large amounts of greenhouse gases that absorb and re-emit energy to heat the earth. The increasing production of greenhouse gases results in more energy being absorbed in the lower atmosphere, which reduces the amount of heat escaping to space and changes the balance of energy in the earth's system (Bush and Lemmen, 2019; Government of Canada, 2019). Vast amounts of CO_2 are produced daily through human activities, since CO_2 is the dominant product released from fossil fuel combustion (Government of Canada, 2019). CO_2 can stay in the atmosphere anywhere from 20 to thousands of years, meaning its effect will continue to be felt even when greenhouse gas emissions from human activity have been eliminated (Riebeek, 2011). This build-up of greenhouse gases is warming the earth at an alarming rate and could increase temperatures to levels never experienced by humans.

2.7 Climate models

The sun's energy is not evenly distributed across the earth; it is the most intense at the equator. To reduce uneven distribution of energy, the atmosphere and ocean transport heat to the polar regions through atmospheric circulation, evaporation and precipitation, and ocean currents (Government of Canada, 2015). This re-distribution creates weather and long-term climate cycles like El-Ninos and La-Ninas. Global Climate Models (GCMs) mimic the complex interactions between earth's atmosphere, land, and ocean by simulating the transfer of energy on earth. Climate models are created by compiling land, ocean, and atmosphere models using mathematical equations to characterize their interactions (NOAA, 2014). Every few years modelling groups from around the world meet with the goal of fostering the development of future climate models to forecast future climate. In September 2008, one of these meetings took place and was called the Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Taylor et al., 2012). At CMIP meetings, scientists run experiments on climate models, which determine their strengths and weaknesses and then they discuss how to improve each model (Taylor et al., 2012). These meetings also provide opportunities for climate scientists to share their knowledge and models with each other, which helps to create more accurate climate models for every part of the world.Every climate model is different and has its own set of strengths and weaknesses. To cope with this variability, Cannon (2015) states that it is desirable to use as many scenarios and climate models as possible. However, this is time consuming and often not practical. As a result, many scientists have begun using automated multivariate statistical algorithms to choose a set of climate models that best span the spread of the data and quantifies variability. Based on Cannon's study (2015) and the KKZ (Katsavounidis-Kuo-Zhang) algorithm, four climate models ACCESS1-0, CanESM2, CNRM-CM5, and INMCM4 were selected for the region in my study.

In the past, researchers used cluster analysis algorithms that would identify clusters of similar climate models. From each cluster one representative climate model would be chosen, the one closest to the centroid of each cluster, and each selected climate model would be used to create an ensemble of climate models used for a study, one ensemble for each region (Cannon, 2015). The issue with cluster analysis algorithms was that it was unlikely to select the same climate models for each region since each researcher has different computational obstacles. This makes it difficult to recommend an ensemble of climate models for each region, and for studies to be comparable to one another for research completed within the same region. As a result, researchers have turned to the KKZ algorithm to select climate models to form a set of climate models recommended for each region. The KKZ algorithm selects climate models that best span the spread of an ensemble, enabling researchers to show the largest amount of variability within their results caused by the variation from climate models (Cannon, 2015). Unlike cluster analysis algorithms, the KKZ algorithm chooses a consistent set of climate models for each region. Researchers can then use this set of climate models specified for their study region and can easily compare it to another study with the same set of climate models.

The Australian Community Climate and Earth System Simulator version 1 (ACCESS1-0) is a general circulation climate model developed at the Center for Australian weather and climate research (CAWCR). The two Australian organizations; the Bureau of Meteorology (BOM) and The Commonwealth Scientific and Industrial Research Organization (CSIRO) collaborated to create the ACCESS1-0 model. The ACCESS1-0 model was created by compiling a land surface model and an atmosphere model with ocean and sea-ice configurations developed by the meteorological office (MET office) in the United Kingdom, and an ocean and sea ice model developed by the National Oceanic and Atmospheric Administration (NOAA) in the United States (Bi et al., 2013). Based on historical simulations done in CMIP5, the ACCESS1-0 model shows similar trends of observed warming in the early and late 20th century and cooling in the mid-20th century. However, the ACCESS model has a cold bias caused by its late start to warming in the late 20th century in the northern hemisphere (Bi et al., 2013; Dix et al., 2013). These results suggest that negative forcing from aerosols are too strong. The studies by Bi et al. (2013) and Dix et al. (2013) show that the ACCESS1-0 model simulates global precipitation and distribution patterns relatively accurately in historical simulations, but like most models have issues predicting cloud cover and cloud feedback and its impact on climate.

The second generation Canadian Earth System Model (CanESM2) consists of the fourth generation atmosphere general circulation model coupled to the Canadian terrestrial ecosystem model and the Canadian model of Ocean carbon (Chylek et al., 2011; Kushner et al., 2018). A study by Chylek et al. (2011) found that the CanESM2 model simulated the 20th century temperatures relatively accurately, but slightly overestimated warming after 1970. Another study by Kushner et al., (2018) assessed the ability of CanESM2 to predict snow and sea ice cover. Kushner's (2018) study found a bias towards excessive seasonal snow cover and precipitation across the Canadian land mass and a greater retreat of snow in the spring when compared to past satellite images. These finding suggest that the model will predict higher precipitation and earlier springs than will likely occur.

The CNRM-CM5 model is the fifth model developed by Centre National de Recherches Météorologiques—Groupe d' études de l'Atmosphère Météorologique (CNRM-GAME) and Centre Européen de Recherche et de Formation Avanceé (CERFACS). CNRM-CM5 is compiled from four different models including the atmospheric model ARPEGE-Climat (v5.2), the ocean model NEMO (v 3.2), the land surface scheme ISBA, and the sea ice model GELATO (Voldoire et al., 2013). A study by Voldoire et al. (2013) evaluated the CNRM-CM5 model and found great improvements in its simulation of past climate and large-scale atmospheric circulation compared to the previous CNRM-CM3 (phase 3) model. Despite its relatively accurate simulations of past climate, CNRM-CM5 underestimates cooling in the 1950-1960's and has difficulty simulating seasonal precipitation and cloud cover. In general, its predictions of seasonal precipitation are regionally variable, and its prediction of cloud cover is biased towards a lack of cloudiness in the

Northern Hemisphere. These shortcomings are relatively minor and overall CNRM-CM5 simulations follow closely with past records.

Phase 4 of the Institute of Numerical Mathematics Climate Model (INMCM4) was created by the Numerical Mathematics of the Russian Academy of Sciences. The climate model INMCM4 consists of atmospheric and general circulation models, and carbon and methane cycles (Volodin et al., 2010). These atmospheric and general circulation models and carbon and methane cycles were created by the Russian Academy of Sciences by using mathematical equations to simulate physical processes of the Earth and Climate System, and carbon and methane cycles and their interactions. A study by Volodin et al. (2011) found that INMCM4 does an excellent job of reproducing past surface air temperature (SAT). On average the SAT is only 0.3°C lower than observed. However, INMCM4 precipitation is somewhat higher than observed and cloudiness is slightly overestimated. Spring sea ice cover is close to observed but fall sea ice is slightly underestimated. Overall, INMCM4 very closely simulates present day characteristics such as solar radiation, surface air temperature, precipitation, snow and sea ice cover, and cloudiness.

2.8 Representative Concentration Pathways

The amount of anthropogenic emissions emitted in the future depend upon changes in human population, climate policy, lifestyle, economic activity, land use, and advances in technology (IPCC, 2014). Based on these factors, the Intergovernmental Panel on Climate Change (IPCC) created Representative Concentration Pathways (RCPs). RCPs are described as a set of scenarios that predict greenhouse gas emissions into the future. There are four RCPs; one low emissions scenario (RCP 2.6), two intermediate emissions scenarios (RCP 4.5 and 6), and one high emissions scenario (RCP 8.5). Each scenario begins with its own set of starting emission values and estimates emissions up to the year 2100. The numbers after each RCP represent the predicted radiative forcing in W/m^2 for 2100. Radiative forcing refers to the change in radiation on earth, caused from a perturbation in the system, such as increases in CO_2 (IPCC, 2014). Positive radiative forcing values indicate surface warming, and negative values indicate cooling. RCPs are used in climate models to forecast future climate based on future predictions of greenhouse gas emissions.Spatial downscaling

GCMs have large spatial resolutions that vary from 100 to 200 km and up. To conduct local scale climate change impact assessments, GCMs must be downscaled to smaller spatial resolutions (Maraun, 2016). Two ways of downscaling climate models include the change factor method and statistical downscaling. The change factor method calculates the difference between observed past climate data and the predicted future climate data from the climate model and uses the difference as a change factor. The major downfall of this method is it only changes the temperature and precipitation and ignores local scale processes. The Pacific Climate Impacts Consortium (PCIC) downscaled the climate models using three different methods. For this study, I chose the statistical processes of bias correction and constructed analogues with quantile mapping reordering to downscale the climate models (PCIC, 2013). All climate models have some biases towards high temperatures, excessive precipitation and cloudiness, etc. To account for these biases, a form of bias correction and quantile mapping was used. Bias correction determines the differences between the observed past and present climate data and the predicted future climate data to create a bias correction factor that is multiplied by the raw future climate data (Maraun, 2016). Change factors and bias correction methods are good techniques to use when correcting biases in temperature, but not when correcting more stochastic variables like precipitation. GCM's are known to have a drizzle problem, meaning that they predict too many low precipitation events and do not capture more realistic large rainfall events followed by periods of no precipitation. To reduce this problem, quantile mapping is used. Quantile mapping uses a distribution that follows the future climate data set closely and replaces values in the raw data that does not follow this distribution (Maraun, 2016; Diaz-Nieto and Wilby, 2005). By using a hybrid method of both bias correction and quantile mapping techniques, the weaknesses of each method are less.

2.9 Future climate change in Saskatchewan

To investigate predicted future climate in Saskatchewan, maps from the Government of Canada (2020) site were downloaded and organized into Figures 2.2, 2.3, 2.4 and 2.5. These maps were created from a multi-model ensemble of 29 global climate models from the CMIP5. The maps show the predicted change in mean temperatures and precipitation for spring, summer, autumn, and winter every 20 years into the future for the RCPs 4.5 and 8.5. These predicted mean changes in temperature and precipitation are based off the 1986-2005 average. Mean temperatures for RCP 4.5 increase for every season as it is projected further into the future (Figure 2.2). Spring, summer, and autumn show predicted temperature increases of 0.5-1 ºC by 2040 to 3-3.5 ºC by 2100 for RCP 4.5.

Winter temperatures in Figure 2.2 are projected to increase the most at around 4-4.5 ˚ºC by 2100. For RCP 4.5, spring precipitation is predicted to increase by 20-30 % in the southern half of Saskatchewan by 2100, and summer precipitation is predicted to decrease by 10-20 % (Figure 2.3).

Predicted autumn precipitation for RCP 4.5, shows a slight increase (10 %) by 2040 and then stays relatively stable thereafter. Winter precipitation for RCP 4.5 is projected to increase 10 % in 2060 to 20-30 % by 2100 for all of Saskatchewan.

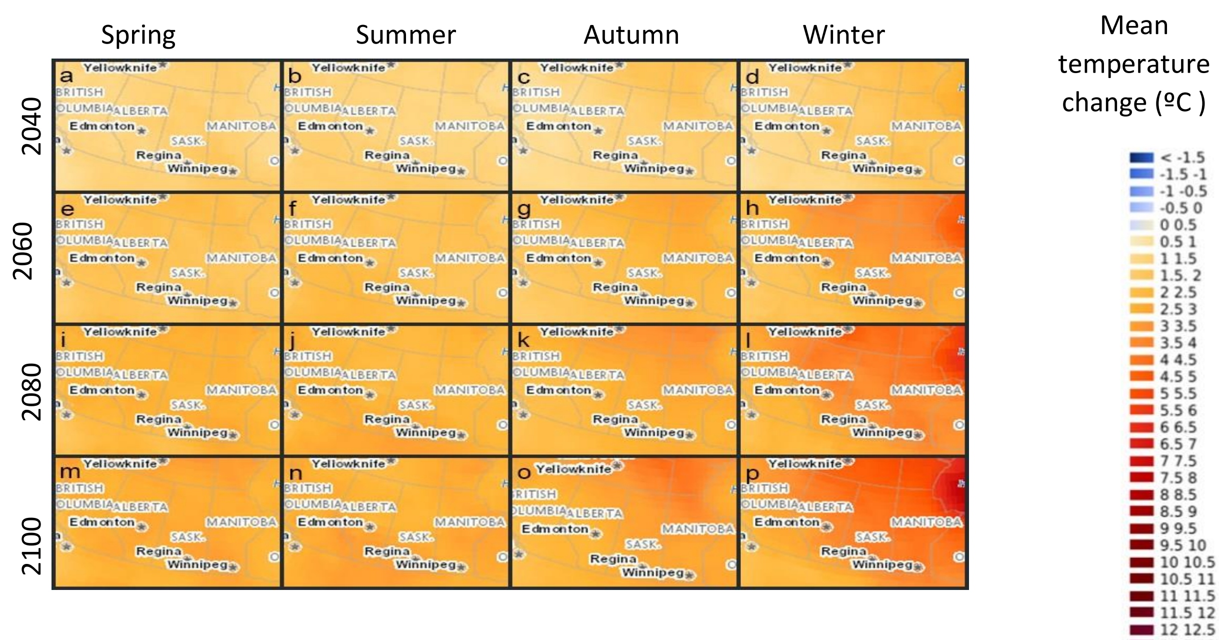

Figure 2.2 An ensemble of 29 climate models forecasting mean temperature

Canada for RCP 4.5 up to the year 2100. All four seasons are projected (Government of Canada, 2020).

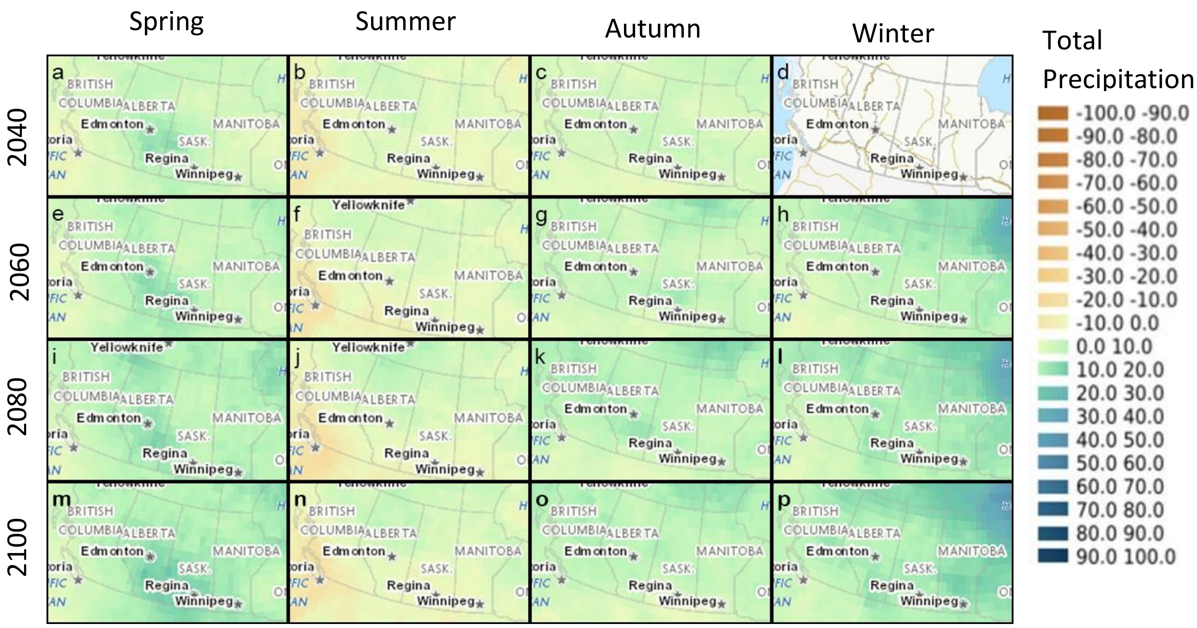

Figure 2.3 An ensemble of 29 climate models forecasting total precipitation change in Western Canada for RCP 4.5 up to the year 2100. All four seasons are forecasted (Government of Canada, 2020).

In Figure 2.4, RCP 8.5 shows larger projected increases in temperature than RCP 4.5 (Figure 2.2). Spring temperatures are predicted to increase from 1.5-2 ºC in 2040 to about 5-5.5 ºC by 2100, and summer and autumn temperature are predicted to increase from 0.5-1 ºC by 2040 to 5.5-6 ºC in 2100 for RCP 8.5. Winter temperature is also predicted to increase about 0.5-1 ºC by 2040 but shows the highest predicted temperature by 2100 at around a 7-7.5 ºC increase. The increases in temperature appear to be more severe in northern parts of Western Canada for spring, autumn, and winter, but summer shows more severe temperature increases in the south. For RCP 8.5, spring and winter precipitation shows increases from 0-10 % by 2040 to 30-40 % by 2100 for all of Saskatchewan (Figure 2.5). Autumn precipitation is also predicted to increase, but only by about 20 % for the southern half of Saskatchewan by 2100. Summer precipitation for most of Saskatchewan is predicted to continually decrease from 0-10 % in 2040 to 10-20 % in 2100 for RCP 8.5 (Figure 2.5). The southernmost parts of Saskatchewan appear to project the highest increases in summer temperature for RCP 8.5.

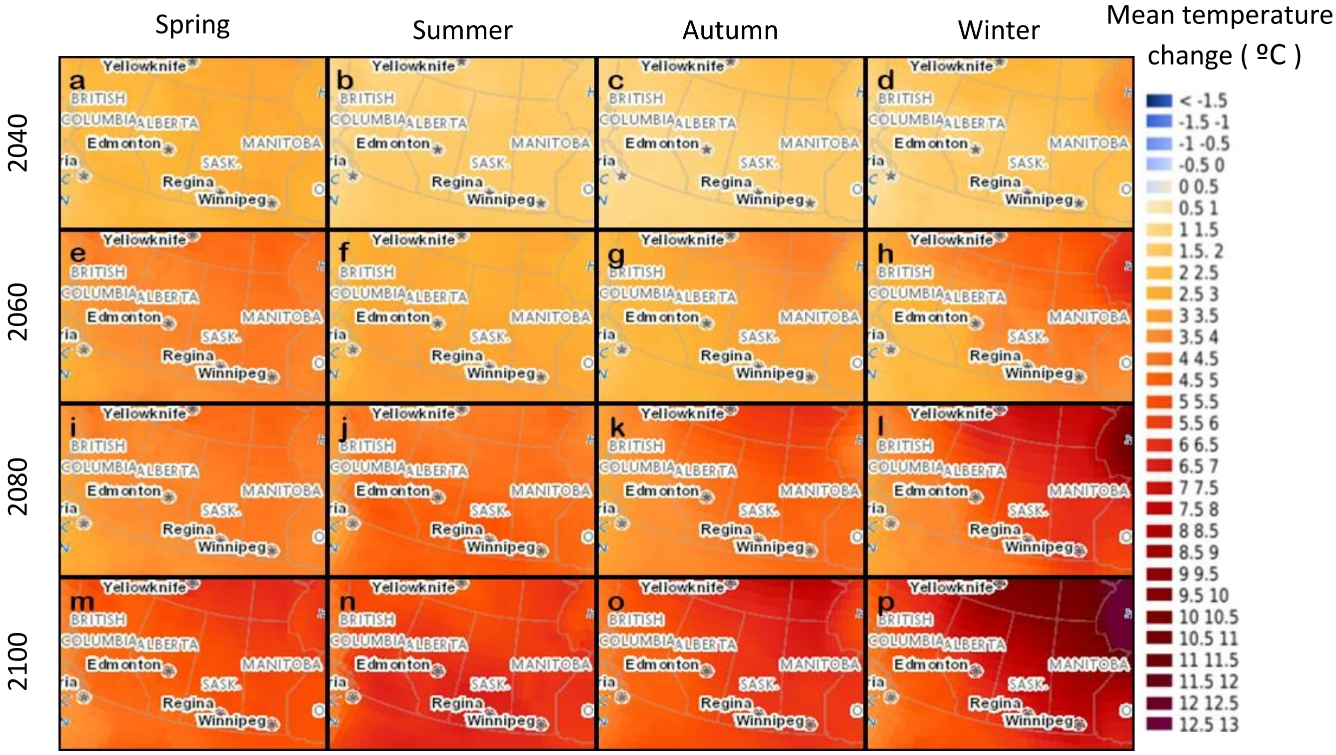

Figure 2.4 An ensemble of 29 climate models forecasting mean temperature change in Western Canada for RCP 8.5 up to the year 2100. All four seasons are forecasted (Government of Canada, 2020.

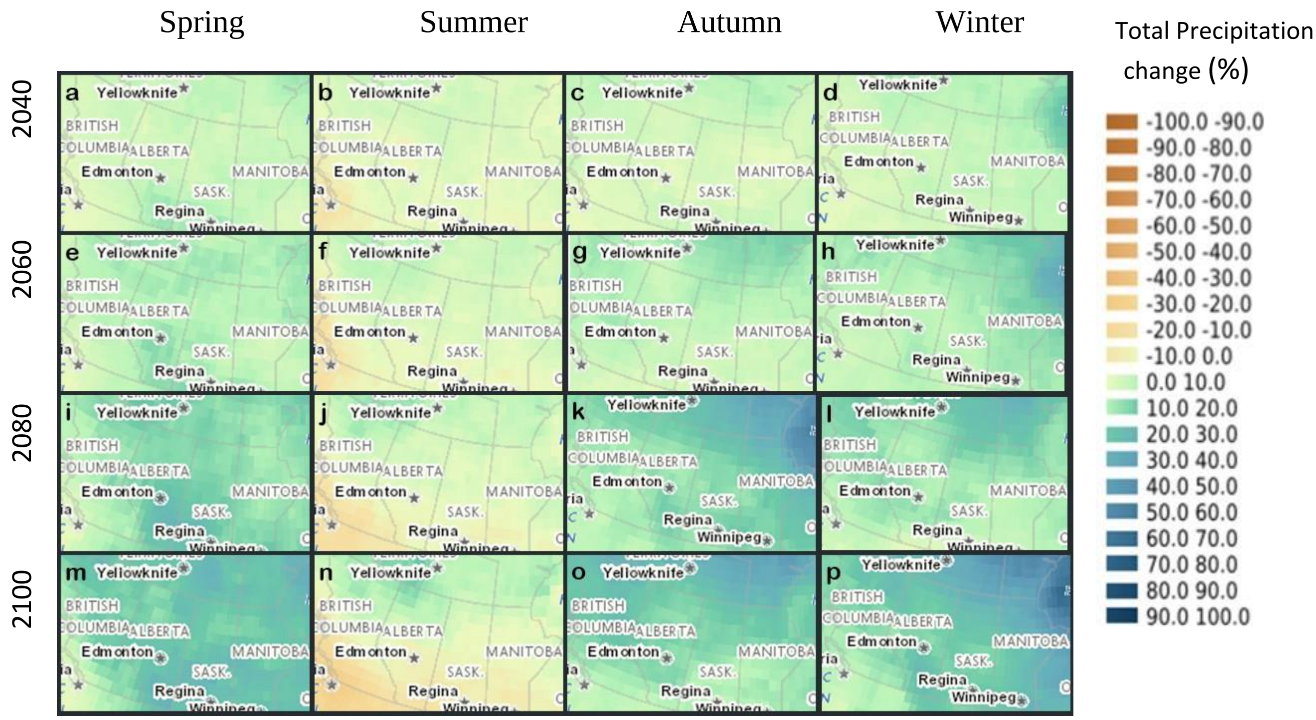

Figure 2.5 An ensemble of 29 climate models forecasting total precipitation change in Western Canada for RCP 8.5 up to the year 2100. All four seasons are forecasted (Government of Canada, 2020).

It should be noted that precipitation is very difficult to predict because of the complex set of variables that control it (Bush and Lemmen, 2019). Although precipitation is predicted to mainly increase for spring, autumn, and winter, it is possible that the rising temperatures and their resulting evapotranspiration could overshadow these moisture increases. Meaning that a positive change in precipitation does not necessarily mean an increase in soil moisture.

2.10 Climate change and shelterbelts

Climate change poses many challenges to agricultural producers in Saskatchewan. Producers will face increased intensity and frequency of extreme weather events, increased pest and disease infestations, and a warmer and drier climate (Barrow, 2009; Gregory et al., 2009). In response to these issues, several studies have named shelterbelts as a tool to help farmers adapt to climate change, by protecting their livestock and crops from the elements (Parry and Carter, 1989;

Easterling et al., 1997; Guo, 2000; Wall and Smit, 2005). More research needs to be conducted on how shelterbelts will fare under climate change throughout Saskatchewan.

Some studies suggest that producers in Saskatchewan could benefit from climate change induced expansion of the growing season, and reason that increasing carbon dioxide levels (CO_2) will enhance plant growth through carbon fertilization (Parry et al., 2004, Barrow, 2009). These studies neglect to include the increased intensity and frequency of violent storms and droughts, increased range and occurrence of pest and disease infestations due to milder winter temperatures, and increased spread in weeds that are associated with climate change (Parry and Carter, 1989; Wall and Smit, 2005; Gregory et al., 2009). Climate change has the potential to both positively and negatively impact producers. Consequently, producers will need to adapt to these changing conditions in order to sustain their livelihoods.

Shelterbelts have been named as a valuable strategy to reduce the negative effects of climate change, and help producers adapt to future climates. An article by Wall and Smit (2005) suggested that sustainable farming practices could help producers manage weather risks that are associated with climate change. In particular, they proposed that shelterbelts could reduce negative impacts from drought by trapping snow, maintaining the water table, and reducing evaporation to keep soil moisture on the land. Wall and Smit (2005) further added that shelterbelts could protect livestock from the intense heat and winds that are predicted to occur under future climates. A study by Easterling et al. (1997) researched the potential of shelterbelts to ameliorate the negative effects of climate change on crop stress at the University of Nebraska Agricultural Research Center near Mead, Nebraska, using the Erosion Productivity Impact Calculator (EPIC). They input increased temperature, evaporation, and wind-speed that are associated with climate change into the EPIC model and compared unsheltered fields to sheltered fields. Their results illustrated that shelterbelts increased crop yields compared to their unsheltered counterparts, which indicated that shelterbelts provide some degree of protection from climate change.

The southern boreal forest is predicted to experience warmer temperatures and increased aridity, which will likely stress tree growth and push the boreal forest boundary northward (Hogg and Schwarz, 1997; Barrow, 2009; Government of Canada, 2017a). Consequently, trees contained within shelterbelts in Saskatchewan will also likely be affected by these climatic changes,

however, there have been no studies conducted on how shelterbelt species will respond to climate change. In
conclusion, the many benefits that shelterbelts provide, their importance in mitigating and protecting producers from climate change, the implications my study could have on carbon sequestration, and the lack of studies regarding the effects of climate change on shelterbelts, provides a sound rationale for my study.

2.11 Dendrochronology and Dendroclimatology

Dendrochronology analyzes tree rings and examines events through time, such as droughts, insect infestations, and changing climatic conditions (Speer, 2012). A subfield of dendrochronology, called dendroclimatology, uses tree rings to understand past climates and analyze climatic changes and their possible effects on trees (Speer, 2012). Trees that tend to be stressed by particular climate variables in an area, provide excellent records of past climate because their tree-ring growth corresponds to the stress. The semi-arid climate of Saskatchewan can provide that stress, which makes Saskatchewan a great place to study dendroclimatology. Dendroclimatology has become increasingly popular in light of climate change, because the historical climate-data recorded in tree rings can be used to help forecast future radial tree growth (Gholami et al., 2017). In fact, dendroclimatology has been used throughout the literature (Phillips and Laroque, 2008; Phillips, 2009; Kennedy, 2010; LaPointe-Garant et al., 2010; Zhang et al., 2012; Davis et al., 2013; Gholami et al., 2017; Maillet et al., 2017) to analyze past climate data and their impact on radial growth to predict how trees will respond to climate in the future. A recent study by Davis et al. (2013) found that the four shelterbelt species used in my study, were useful for conducting dendrochronological studies. This indicates that using dendroclimatology to predict the effects of climatic changes on these shelterbelt species will be an effective method.

2.12 Agriculture and Greenhouse Gases Program - phase 1

Phase one of the five-year Agriculture and Greenhouse Gases Project (AGGP1) commenced in 2011. The first phase of the project determined that the nine shelterbelt species of interest were all useful for dendrochronology purposes and ranked them in order from most useful to least useful (Davis et al., 2013). Once it was established that nine species was too large of a sampling base, the AGGP crew mapped and quantified a shelterbelt inventory of the six most common shelterbelt species; white spruce, Scots pine, green ash, hybrid poplar, Manitoba maple (*Acer negundo*), and caragana (*Caragana arborescens*) across Saskatchewan (Amichev et al., 2015). Using dendrochronological techniques, the projected growth and biomass of these six species were estimated with Physiological Processes Predicting Growth (3PG) model. The resulting 3PG data was then put into a carbon budget model of the Canadian Forest Sector (CBM-CFS3) carbon dynamics model to estimate the carbon stocks of the six species, and predict potential future carbon sequestration (Amichev et al., 2016a; b). However, this data does not take into account the potential effects of climate change on future shelterbelt growth and carbon sequestration.

These studies from AGGP1 raised almost as many questions as they answered. In response to these new questions, a phase two of AGGP (AGGP2) commenced in 2017. Phase two aims to create a management toolbox to aid landowners with the maintenance and planting of their shelterbelts, using past information collected in AGGP1 and information obtained in AGGP2 to do so.

2.13 Selected shelterbelt species

Four shelterbelt species; white spruce, Scots pine, hybrid poplar, and green ash were selected for this study. These species represent four of the six species that were studied in AGGP1 and were chosen so that the samples collected in AGGP1 could be reused for this study. The two species from AGGP1; caragana and Manitoba maple were not included in this study for a variety of reasons. Firstly, caragana is a shrub that produces many stems, most of the stems do not grow older than the necessary 30 years of age in order to crossdate, making this species difficult to use. Manitoba maple was not included in the study, simply because of the lack of time associated with this study and the fact that the cores of older trees tend to be rotten, making sample analysis more difficult.

These four shelterbelt species were identified in a study by Davis et al. (2013) as being useful for dendrochronological purposes because of their intermediate to high inter-series correlation, and sensitivity to climate. This makes them ideal for studying climate-growth relationships. Each species is adapted to different climatic conditions and soil textures, indicating that these species will likely be best adapted to different regions across the study area. These different adaptations will provide a wide range of possible future outcomes for each species under future climates. The trees were required to be a minimum of 40-years old in order to establish a significant crossdate between trees. Crossdating refers to the process of matching ring-width patterns between cores of the same tree and cores of different trees from the same site in this instance (Speer, 2012). Forty-year old trees are also required to evaluate climate-growth relationships, because tree-ring growth must be compared to a relatively long historical time-series of climate data to determine a common signal among trees at a site.

White spruce is a tall, slow growing, coniferous tree that is native to all the provinces in Canada. It grows best in full sun, on well-drained, moist loam soils, and is adapted to the northern boreal forest and typically does not extend much farther than the boreal transition zone, because it does not perform well on dry and exposed sites (Agriculture and Agri-Food Canada, 2006). White spruce is often used as a farmyard shelterbelt because its shallow and somewhat competitive root system is not suited for field shelterbelts. Since white spruce is native to Canada, they provide excellent habitat for wildlife, and are often planted to attract wildlife and beautify a yard. A study by Davis et al. (2013) identified white spruce as the most useful shelterbelt tree for dendrochronology purposes because of its high inter-series correlation, and mean sensitivity to climate, indicating that white spruce have a strong common growth signal within and between trees, and that its growth is highly influenced by climate. The non-porous wood-structure of white spruce, which is characteristic of gymnosperms, makes the ring boundaries clearly defined, because of the increasing cell-wall thickness of the tracheids in the latewood (Speer, 2012).

Scots pine is a tall, moderately fast-growing conifer that was introduced from Europe and Asia (Agriculture and Agri-Food Canada, 2006). The Shelterbelt Centre at Indian Head improved the seed strain so that Scots pine are adapted to all of the ecoregions within Saskatchewan. Scots pine prefer moist, well-drained soils, but are also adapted to dry, sandy sites, and are not often used in farmyard shelterbelts (Agriculture and Agri-Food Canada, 2006). Because Scots pine is an introduced species, it provides less value for wildlife. Scots pine was ranked as the ninth most useful species for dendrochronology purposes in a study by Davis et al. (2013), because of its low, but significant, inter-series correlation, meaning that species at a site tend not to correlate well with each other. However, Scots pine had the third highest mean sensitivity value, indicating that Scots pine's radial growth is highly influenced by climate. Despite Scots pine's low inter-series correlation, it is still considered to be useful for dendrochronology purposes.

Similar to white spruce, Scots pine's ring boundaries are clearly defined because of its non-porous wood structure (Speer, 2012). Hybrid poplar is available as several different clones, however, selecting one clone to sample would be extremely difficult, since differences between clones are nearly impossible to identify in the field. Therefore, I sampled every type of hybrid poplar and accepted some inherent variability. Hybrid poplar was chosen for this study because it has been identified as the shelterbelt tree with the largest carbon sequestration abilities due to its fast-growth rate (Amichev et al., 2016a). Hybrid poplars perform best on moist, loam soils, but are adapted to all ecoregions and are considered to be relatively hardy. They are sensitive to prolonged drought and flooding, and do not tolerate saline soils. Hybrid poplars are a popular farmyard shelterbelt tree and are almost never used in field shelterbelts because of their competitive root system.

Their diffuse-porous wood structure makes ring identification difficult, because the large number of vessels produced in the wood have no relationship to the ring structures (Speer, 2012). Although their rings are difficult to see, hybrid poplar is considered to be useful for dendrochronology purposes because of its high inter-series correlation (Davis et al., 2013). Green ash is a medium-tall, moderately fast-growing deciduous tree that is native to southern Canada. The Shelterbelt Centre at Indian Head improved the seed strain, and the species is adapted to all of the ecoregions of Saskatchewan, except the mixed grassland (Agriculture and Agri-Food Canada, 2006). Green ash prefers loam or clay-loam sites that are in full sun, and the species is known to be hardy and moderately to highly drought resistant. Its deep, and non-competitive root system make green ash a popular field shelterbelt, but green ash is limited to some degree because of its susceptibility to 2,4-D and glyphosate damage (Agriculture and Agri-Food Canada, 2006). Green ash is also threatened by the emerald ash borer, which is yet to be found in Saskatchewan, but when it reaches Saskatchewan has the potential to decimate green ash stands (Government of Saskatchewan, 2017). Green ash's ring-porous wood structure uses energy reserves from the previous growing season, to form rows of vessels at the beginning of the growing season, which makes it relatively easy to identify ring boundaries (Speer, 2012). A study by Davis et al. (2013) identified green ash as the fifth most useful shelterbelt species for dendrochronology purposes because of its high inter-series correlation value, but low abundance and mean sensitivity value. These four species are all commonly found throughout Saskatchewan as farmyard and/or field shelterbelts. Each species is useful for dendrochronology purposes, and hence are suitable for this study. This shelterbelt background knowledge will be helpful when interpreting results, by providing potential explanations about past- and predicted-future growth trends at a site.

2.14 Creating future climate models to forecast radial growth

Tree growth is influenced by a multitude of factors including temperature, precipitation, soil moisture, depth to water table, solar radiation, topography, and soil texture and nutrients (Toledo et al., 2011). In Saskatchewan, climate limits physiological tree growth, resulting in a strong tree growth-climate relationship. Because of this strong relationship, it has become increasingly popular to use the tree growth-climate relationship to predict future radial growth under future climates (Laroque, 2002; Chhin et al, 2008; Phillips and Laroque, 2008; Lapointe-Garant et al., 2010; Williams et al., 2010; Huang et al., 2013). Most tree-ring studies that predict the impact of future climate, usually assume there's a linear and constant relationship between tree growth and climate (Laroque, 2002; Chhin et al., 2008; Phillips and Laroque, 2008; Williams et al., 2010; Huang et al., 2013). This type of tree growth-climate relationship is modelled, and the model is used to predict future growth.

Typically, temperature and precipitation climate variables for the current and previous growing season (April-September) are used in future growth models (Laroque, 2002; Chhin et al., 2008; Phillips, 2009; Williams et al., 2010). However, previous season winter temperatures and precipitation also influence growth. Studies by Hänninen (2006), Bigler and Bugmann (2018), and Nanninga et al. (2017) examined the impact that climate-induced warming in the winter could potentially have on trees. These studies suggest that climate warming will increase the risk of frost damage in trees by causing dehardening and potentially budburst during climate-induced winter warm spells and early springs. If a frost occurs during budburst, the affected tree often uses its remaining resources to bud later again in the season, ultimately weakening the tree and reducing growth. A study by Nanninga et al. (2017) found that climate warming can induce advanced budburst in some trees but will delay budburst in other species because they require more winter chilling to break dormancy. This delay will reduce the growing season for these species and decrease their productivity. Previous winter precipitation also plays an important role in tree growth because winter snowpack provides insulation to reduce soil and root freezing, and winter runoff/moisture in the spring. Figures 2.2 and 2.4 predict that winter temperatures will experience the most increases under climate change, which could impact tree budburst, frost risk,and snowpack. Therefore, previous growing season winter temperature and precipitation are important variables to include in future growth models.

2.15 Concluding remarks

Shelterbelts were important in the past to combat erosion and protect soil health and are still important today because they provide mitigation strategies for many problems that society currently faces. However, current research has not yet determined the potential effects of climate change on shelterbelts. To ensure that both producers and the public can benefit from shelterbelts, the effects of climate change on shelterbelts must be determined. My study aims to help landowners choose the shelterbelt species that will be best adapted to their area of Saskatchewan under future climates using dendroclimatological techniques.

3 MATERIALS AND METHODS

3.1 Sites and experimental design

Sites were sampled across the Brown, Dark Brown, and Black soil zones of Saskatchewan. The AGGP1 crews collected tree cores from 101 sites of the four selected shelterbelt species across the southern half of Saskatchewan. Specifically, 15 hybrid poplar, 22 green ash, 18 Scots pine, and 46 white spruce sites were collected. A form of opportunistic sampling was used to select these sites. Each site selected by the AGGP1 crew had at least 20 trees of one or more of the study species that were 40-years old or older and they obtained permission from the landowner to sample the trees. Previous studies have concluded that opportunistic sampling is the only feasible way to collect tree cores, especially on private property where permission is needed (Phillips and Laroque, 2008; Phillips, 2009; Kennedy, 2010; Davis et al., 2013; Maillet et al., 2017). I put the AGGP1 sites through a quality control check, where many were discarded because they were either not old enough (<40 years), would not crossdate, there were not enough samples in the final chronology (<30 samples), or the files or tree-cores had been lost. After the quality control check there were 18 green ash, 7 hybrid poplar, 17 white spruce, and 7 Scots pine sites that could be used for my analysis.

My sampling design was based on both geographic spread of the samples and opportunistic sampling. Geographic spread sampling aims to provide an even coverage over a specific area in order to capture variability across a landscape. Phillips and Laroque (2008) used a similar form of opportunistic sampling for their dendrochronology research. Speer (2012) describes opportunistic sampling as an often-necessary form of sampling because of the need for permission to sample. In this case, I was interested in capturing the climate variability across the three southern-most soil zones of Saskatchewan. The climate throughout Saskatchewan is variable and highly localized, for example, Saskatoon and Regina are in the same soil zone, but the homogenized monthly climate data from the Government of Canada (2017b) website illustrates that on average Regina receives less precipitation and higher temperatures than Saskatoon. It is important to capture this type of climatic variability throughout Saskatchewan using a geographic spread of sampling points, to determine how each species will be adapted to different regions and soils throughout the study area under future climates (Lamb, personal communication, January 2018). On Google Earth Pro, a layer of AGGP1 quality control checked sites was created. For each species, large gaps between sites were identified, and for each gap, a 200 km grid square was drawn around the area. Using the

PFRA database, sites that met my site selection criteria (selected shelterbelt species 40 years or older) were added as a layer onto Google Earth (2020). Each selected 200 km square contained potential sites for each shelterbelt species. These potential sites were organized into randomized call lists and the AGGP2 crew called landowners in this randomized order to ask for permission to sample their shelterbelts. If the trees were confirmed to have met all the site selection criteria and permission was granted, then I made plans to visit the site.

In the summer of 2017, an additional nine sites were collected (five white spruce, three hybrid poplar, and one Scots pine site) using opportunistic sampling in the Dark Brown soil zone of Saskatchewan. Of these nine sites, all the hybrid poplar sites were either too young to process, or the rings were too difficult to see because of tree rot, and two of the white spruce sites could not be used because of crossdating issues. In the summer of 2018, 16 more sites were collected; five green ash, three hybrid poplar, three white spruce and five Scots pine in the Brown, Dark Brown, and Black soil zones of Saskatchewan. Of these 16 sites only one hybrid poplar site had to be discarded because of tree rot. A total of 68 sites were used in the study: 23 white spruce, 23 green ash, 13 Scots pine, and 9 hybrid poplar. Of these 68 sites, 49 were collected from AGGP1 crews and 19 from AGGP2 crews.

Each site was labelled with a unique identifier. The first two numbers of the label indicate the year the site was sampled in. The next letter of the label provides an alphabetically ordered list of when in the year each site was sampled. For example, the letter A indicates the site was the first set of cores that was collected that year. The L that indicates that the tree was “live” when the tree cores were taken. The last set of three letters and numbers is a code that identifies which species it is. The code 200 indicates that it is white spruce, S00 is Scots pine, M00 is green ash, and N00 is hybrid poplar.

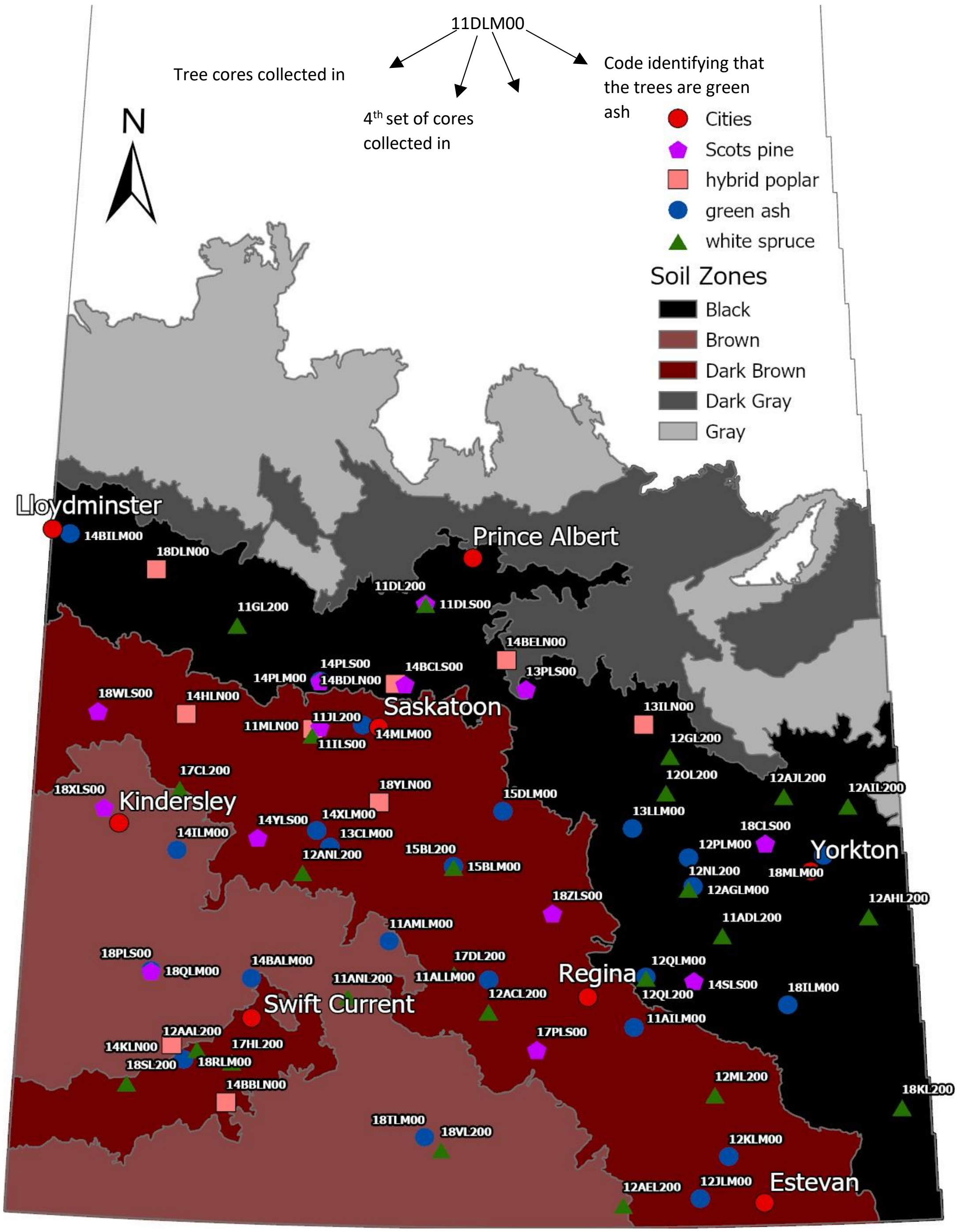

Figure 3.1 Study site locations indicated by four different symbols. Each shelterbelt species is identified by a different coloured symbol and each site is labelled with an individual identifier.

3.2 Sampling procedure and storage

The same sampling procedure that was used in AGGP1 was used in 2017 and 2018. At each site 40 tree cores were collected. Twenty trees were sampled with two cores taken per tree at each site, at breast height (1.3 m) and at ninety-degree angles. A 5.1 mm increment borer was used and were cored into the tree just past the pith. In the instance of a leaning tree, we took cores from the sides of the tree (neither upslope nor downslope) at 180 degrees to avoid coring into reaction wood. Reaction wood refers to the extra material (larger rings) that the tree grows on either the upper or lower side of the slope or lean (depending on the tree species), to account for leaning to try to maintain a vertical position (Speer, 2012). The purpose of collecting two cores per tree is to directly compare the cores of each tree to ensure that ring anomalies are minimized (Kennedy, 2010; Speer, 2012). For example, one core of a tree may have a ring that is missing, whereas the other core from the tree may not. This missing ring would be accounted for when crossdating to ensure pattern matching was accurate.

The cores were stored in straws with the ends taped shut. Each tree core pair was taped together, and all the cores at one site were bundled together, taped, and labelled. Back at the lab, tree cores were glued to slotted plywood mounting boards, labels transferred, and subsequently sanded with progressively finer sandpaper, and buffed to more clearly see the tree rings and the cellular structure of the cores. It was not necessary to dry the tree cores before gluing them to mounting boards. Conifers were sanded with 80 to 400 grit sandpaper, since they have a non-porous wood structure with more clearly defined tree-ring boundaries. Whereas deciduous trees have porous wood structures, which makes the rings difficult to see and thus were sanded with 80 to 800 grit, and then buffed to remove the fine particles from the porous cells on a buffing wheel (Speer, 2012).

3.3 Analysis of the tree cores

A series of steps using three computer programs were used to determine the master chronology for each site. To start, I measured the tree rings using a Velmex stage system (Speer, 2012) and the Measure J2X computer program (VoorTech, 2016). These measurements were then crossdated using COFECHA (Grissino-Mayer, 2001) and detrended and standardized with ARSTAN to make the master chronology (Cook and Holmes, 1996).

The purpose of counting and measuring tree rings is to determine the age of the trees and their sensitivity to climate (Speer, 2012). Environmental limitations such as drought, reduce tree-ring growth, resulting in a smaller tree ring. The more variable the ring width is, the more sensitive the trees are to environmental limitations. I used the Velmex stage system with a precision of 0.001 mm and the Measure J2X computer program to measure, record, and count the tree rings. Program COFECHA was used to crossdate and determine a pattern of growth at a site. The ring-width measurements of each year was then averaged together to create a master chronology for the specific site, and each tree core was analyzed against this master chronology (excluding the tree core being analyzed) to produce a Pearson product-moment correlation coefficient or a mean series intercorrelation (MSI) – r values (Grissino-Mayer, 2001). These r-values describe the linear relationships between the master chronology and each individual core, based on the analysis of 30-year segments with a 15-year overlap. The r-values must be greater than 0.423 to be significant at a 99% confidence interval (Grissino-Mayer, 2001). This program also uses crossdating to ensure that each individual tree ring corresponds to the correct year by detecting potential human errors and/or ring anomalies. If a core does not correlate to the master chronology at the significant level, COFECHA uses a 20-year window (-10 to +10 years) to determine where the core could potentially correlate better to the master chronology. If there was a place where the core correlated better with the master, the core was remeasured to ensure there were no human made errors. If there were no human made errors and there was a ring missing or a ring anomaly was detected, a program called EDRM (Speer, 2012) was used to move the chronology back or forth a year, instead of remeasuring the core to account for the missing ring or anomaly. Once corrected, the core was put back into COFECHA to check if the fixed error contributed to a better overall correlation value. Once the potential errors had been fixed, and the overall group correlation value was over 0.423, the resulting tree-core measurements were put into ARSTAN. If a tree core was damaged, rotten, or in some way not measurable, the core was discarded and was not part of the master chronology.

Program ARSTAN was used to standardize and detrend the tree-ring measurements. A negative exponential or best fit detrending spline was used to remove age-related growth by scaling the ring-width curve so that ring widths only reflect environmental limitations.

The robust mean function in ARSTAN was used to take an average of the ring widths from each tree core to create a final master chronology. This chronology is standardized (indexed), to create a line graph that illustrates how much the ring widths of the master chronology vary above and below the mean of 1.0. Tree cores collected from AGGP1 had already been measured, and crossdated, and I only needed to standardize them using the methods described above.

3.4 Past and future climate data

Homogenized monthly past climate data from climate stations across southern Saskatchewan, specifically precipitation and maximum temperature data was collected from the Government of Canada website (2017b). Homogenized climate data refers to climate station data where non-climatic factors such as instrument changes and station relocation were removed using statistical procedures (Government of Canada, 2017b). Often climate data was missing for certain years from specific climate stations. To resolve this issue, climate data from the nearest surrounding climate stations (2 to 3 stations) were averaged to fill in the missing data. In the regression model, max temperature and precipitation data from the nearest climate station (Appendix Figure A.1 and Table A.1) to the site consisting of monthly data from April -September for the current year and monthly data from January – December (the whole year) from the previous year were used, totaling 36 variables. Climate data from the previous year of growth was used because of autocorrelation. Autocorrelation is the concept that the previous year's climate affects the trees current year of growth, which is well accepted in dendrochronological studies (Fritts, 2006; Phillips, 2009; Lapointe-Garant et al., 2010; Speer, 2012; Hogg et al., 2013). This climate data was analyzed against the residual master chronology created by ARSTAN for each site using a linear regression in R (version 3.5.3), to create the model to predict future-radial growth.

The four climate models used to obtain future climate data were; ACCESS1-0, CanESM2, CNRM-CM5, and INMCM4 (Taylor et al., 2012; Cannon, 2015; Bonsal, personal communication, November 2018). For each climate model the RCPs 4.5 and 8.5 were used to predict future climate forcing. To downscale the future climate data to a gridded resolution of about 10 km, the Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) method of downscaling was used (Bonsal, personal communication, November 2018; PCIC, 2019). The BCCAQ method of downscaling had already been computed by the Pacific

Climate Impacts Consortium (PCIC), and as a result the future daily downscaled max temperature and precipitation data for each of the four models and RCPs was simply downloaded from the PCIC website (PCIC, 2013). This daily climate data was then converted to monthly data using MATLAB (McConkey, personal communication, December 2018).

3.5 Linear regression model

For each site a linear model between ring-width (standardized residual chronology created in ARSTAN) and current and previous maximum temperature and precipitation (from climate stations) was created using the program R (version 3.5) (Appendix R Script A.1). Insignificant climate variables (p value <0.10) were removed from the linear model in a stepwise manner using Akaike's Information Criterion (AIC), so that anywhere from three to six climate variables were used in the final models. The normality of the residuals were evaluated by Q-Q plots to ensure that the data was normal.If the model had an R-squared value equal to or greater than 0.30 it would be accepted. The reason for this cut-off of 0.30, was because an R-squared value lower than 0.30 indicated that the trees at the site did not correlate well with climate, and thus would not provide an accurate prediction of how climate will affect future growth. The model was then cross-validated using k-fold cross-validation in R (version 3.5), to ensure the model was not over or underfitted. The purpose of cross-validation is to determine how well the model performs in the real world. The goal was to lower the cross-validation score as much as possible while still maintaining a high R-squared value. Generally, models were accepted if they had a change of ≤ 0.15 when they were cross-validated, and a cross-validated R-squared of 0.20. A variance inflation factor (VIF) was used to determine if there was any collinearity, if the VIF between the variables was higher than 5, then the variables were considered collinear (Hair et al., 2011). Nearly all the sites did not have collinearity, but for the few sites that did, the collinearity was caused by having the same month temperature and precipitation data within the model. To eliminate the collinearity, the climate variable (precipitation or temperature) with the lowest significance was removed from the model.

Once created, the linear model identified which past climate variables most influenced the growth of the species at each site. These selected climate variables (e.g. current July temperature) and their coefficients, along with predicted future climate data from each RCP and climate model were used to calculate predicted future radial growth in R (version 3.5) for each site. The following multiple linear regression equation was used in R (version 3.5) to calculate predicted future growth for all sites.

$$y = b_0 + b_1*x_1 +\ldots..+b_n*x_n$$

The y represents future growth (dependent variable), b_0 is the y intercept of the linear regression, b_1 is the coefficient of a significant climate variable included in the model, and x_1 is the climate variable value (precipitation or temperature).

The relative weights of each climate variable used in the future growth model was determined using the relweight function in R (version 3.5). Relative weights estimate the percent increase in R-squared when a climate variable is added. For example, relative weights can tell you that current July temperature accounts for 38% of the R-squared. It will also show which climate variable has the greatest relative influence on growth.

3.6 Mapping

Future growth data was organized by averaging the predicted radial growth every 25-years (2011-2024, 2025-2049, 2050-2074, 2075-2100) into a spreadsheet using the program Excel.Past growth was also averaged and added to the spreadsheet, and the difference between past growth and future growth was calculated using the raster calculator in ArcGIS pro (version 2.6). As a result, the maps shown in this study show the difference between past and predicted future radial growth of the trees.

T-tests between the average past growth and the predicted growth for each species and model every 25-years into the future were conducted using R (version 3.5). Firstly, the normality of the data was checked using the Shapiro-Wilk’s method, to ensure that the data met the assumptions of a t-test. The p-values of these t-tests were added to predicted growth maps and to tables to determine if there was a statistical difference between past growth and predicted future growth.

The relative weights for each site were organized into spring (MAM), summer (JJA), autumn (SON), and winter (DJF) precipitation and temperature categories, both previous and current growth year climate variables were combined and added to the spreadsheet. This spreadsheet was put into ArcGIS pro, and a spline was used to create a raster of the past and predicted future growth and relative weights.

A spline was chosen to create the raster in ArcGIS pro (version 2.6) because it is considered the best raster for small ranges of values, thus it was sensitive enough to detect the miniscule changes in radial growth where small changes indicate extreme decreases or increases in growth (ESRI, 2020). Firstly, rasters of the averaged past growth and averaged 25-year future growth subsets were created, then a raster calculator was used to subtract the difference between past and predicted future growth. Contour lines at intervals of 20% were put into the relative weights maps so that changes could be seen more clearly. The purpose of mapping relative weights was to determine where each climate variable had the largest influence on radial growth. The scale used in the relative weights maps ranges from 0-100%, since relative weights are expressed as how much (percent) each climate variable contributes to the R-squared (total variance in tree-growth explained by climate). In summary, the relative weights maps show how much of an influence each climate variable has on growth throughout the study area, and the predicted future growth maps show the difference between past and future predicted growth. These finished maps were then organized inAdobe Photoshop CC (2020).

4 RESULTS

4.1 General chronology characteristics

All 68 sites had chronology lengths $\geq$ 40 years, and mean series intercorrelation (MSI)R-values well above the minimum value of 0.4226 (Tables 4.1, 4.2, 4.3, 4.4) for significance at the 99% confidence interval based on 30- year overlapping segments (Grissino-Mayer, 2001). All species had average mean sensitivity (AMS) values greater than 0.30, which is considered a high mean sensitivity value based on a scale developed by Grissino-Mayer (2001). This scale states that trees with a mean sensitivity higher than 0.30 exhibit high climatic sensitivity.

Green ash sites tended to be older, averaging 65 years at breast height, and were highly correlated to same site samples resulting in an average MSI value of 0.660 (Table 4.1). This MSI value is the second highest of the shelterbelt species and falls behind white spruce as the strongest correlation between samples at the same location. Green ash chronologies had the lowest overall average autocorrelation and AMS values of all four shelterbelt species at 0.601 and 0.315 respectively (Table 4.1). The R-squared values explaining the relationship between green ash ring width and climate ranged from 0.598 to 0.280 and had an overall average R-squared value of 0.396. When the models were cross-validated, they had an average explanatory power of 0.283 (Table 4.1).

Table 4.1 Site-specific location and chronology information for each green ash site, organized from south to north sites. Chron. Length = Chronology length, MSI = Mean series intercorrelation: measures strength of correlation between samples taken from the same site, based on 30 year overlapping sections, Auto Corr. = Auto correlation: measures effect of the previous year's growth on current year growth, AMS = average mean sensitivity: indicates the year-to-year variability in radial growth within the chronology, R-squared: measure of how much the variance in radial growth is explained by climate, Cross-Val R-squared: cross-validated R-squared: how much the variance in radial growth is explained by climate when used on other sites.

Green ash Site Name	**Latitude**	**Longitude**	**Chron. Length**	**MSI**	**Auto Corr.**	**AMS**	**R-Squared**	**Cross-Val R-Squared**
12JLM00	49.175000˚	-103.586694˚	62 yrs. (1950-2011)	0.746	0.569	0.377	0.503	0.423
12KLM00	49.435611˚	-103.314361˚	75 yrs. (1937-2011)	0.726	0.523	0.345	0.420	0.334
18TLM00	49.566450˚	-106.14055˚	45 yrs. (1973-2017)	0.707	0.489	0.376	0.373	0.246
18RLM00	50.005770˚	-108.41811˚	99 yrs. (1920-2018)	0.606	0.707	0.300	0.331	0.206
11AILM00	50.255528˚	-104.182139˚	72 yrs. (1939-2010)	0.654	0.593	0.317	0.366	0.285
18ILM00	50.378660˚	-102.722336˚	48 yrs. (1970-2017)	0.638	0.74	0.250	0.450	0.332
14BALM00	50.534667˚	-107.815694˚	88 yrs. (1926-2013)	0.533	0.578	0.322	0.339	0.227
18QLM00	50.555170˚	-108.77271˚	55 yrs. (1964-2018)	0.637	0.621	0.277	0.341	0.233
11ALLM00	50.555861˚	105.559028˚	89 yrs. (1922-2010)	0.649	0.488	0.320	0.391	0.281
12QLM00	50.571417˚	-104.063028˚	76 yrs. (1936-2011)	0.683	0.553	0.326	0.366	0.281
11AMLM00	50.791167˚	-106.514528˚	55 yrs. (1956-2010)	0.694	0.602	0.338	0.308	0.196
12AGLM00	51.135833˚	-103.597111˚	56 yrs. (1956-2011)	0.653	0.635	0.299	0.548	0.453
15BLM00	51.266833˚	-105.907800˚	52 yrs. (1963-2014)	0.707	0.515	0.341	0.598	0.454
18MLM00	51.310010˚	-102.33551˚	50 yrs. (1968-2017)	0.625	0.589	0.308	0.423	0.279
12PLM00	51.316556˚	-103.635861˚	57 yrs. (1955-2011)	0.728	0.683	0.263	0.504	0.397
14ILM00	51.319278˚	-108.583000˚	71 yrs. (1943-2013)	0.689	0.535	0.317	0.359	0.261
13CLM00	51.372722˚	-107.105639˚	53 yrs. (1960-2012)	0.724	0.59	0.343	0.363	0.237
14XLM00	51.473778˚	-107.239139˚	72 yrs. (1942-2013)	0.586	0.594	0.321	0.278	0.192
13LLM00	51.505333˚	-104.175306˚	45 yrs. (1968-2012)	0.710	0.804	0.279	0.430	0.301
15DLM00	51.615730˚	-105.433322˚	93 yrs. (1922-2014)	0.589	0.691	0.289	0.359	0.271
14MLM00	52.143900˚	-106.820189˚	91 yrs. (1923-2013)	0.563	0.698	0.304	0.351	0.149
14BILM00	53.262389˚	-109.825389˚	48 yrs. (1966-2013)	0.537	0.728	0.312	0.419	0.278
14PLM00	52.413344˚	-107.252511˚	44 yrs. (1970-2013)	0.784	0.455	0.317	0.280	0.203
Average	NA	NA	65 yrs.	0.660	0.601	0.315	0.396	0.283

The average age of hybrid poplar trees in the study was 55 years, the oldest site being 98 years and the youngest 41 years. Hybrid poplar chronologies had relatively high MSI, autocorrelation, and AMS values at 0.602, 0.700, and 0.359 respectively. In fact, the autocorrelation value ranked the highest of the four shelterbelt species. The average R-squared value ranked the lowest of the four shelterbelt species at 0.351 and when cross-validated was 0.247 (Table 4.2).

Table 4.2 Site-specific location and chronology information for each hybrid poplar site, organized from south to north sites. Chron. Length = Chronology length, MSI = Mean series intercorrelation: measures strength of correlation between samples taken from the same site, based on 30 year overlapping sections, Auto Corr. = Auto correlation: measures effect of the previous year's growth on current year growth, AMS = average mean sensitivity: indicates the year-to-year variability in radial growth within the chronology, R-squared: measure of how much the variance in radial growth is explained by climate, Cross-Val R-squared: cross-validated R-squared: measures the predictive power of the model.

Hybrid poplar Site Name	**Latitude**	**Longitude**	**Chron. Length**	**MSI**	**Auto Corr.**	**AMS**	**R-Square**	**Cross-val R-Square**
14BBLN00	49.748500°	-108.007250°	80 yrs. (1934-2013)	0.537	0.673	0.331	0.311	0.217
14KLN00	50.098800°	-108.541600°	42 yrs. (1972-2013)	0.575	0.759	0.339	0.296	0.208
18YLN00	51.659699°	-106.640811°	49 yrs. (1969-2017)	0.597	0.715	0.328	0.308	0.183
11MLN00	52.110389°	-107.309667°	98 yrs. (1913-2010)	0.703	0.718	0.313	0.432	0.354
13ILN00	52.156861°	-104.052583°	43 yrs. (1970-2012)	0.676	0.699	0.283	0.419	0.345
14HLN00	52.173250°	-108.560528°	41 yrs. (1973-2013)	0.544	0.602	0.484	0.413	0.265
14BDLN00	52.406167°	-106.507056°	51 yrs. (1963-2013)	0.602	0.655	0.423	0.318	0.208
14BELN00	52.565667°	-105.408583°	48 yrs. (1966-2013)	0.528	0.713	0.365	0.276	0.182
18DLN00	53.070533°	-108.936018°	47 yrs. (1971-2017)	0.653	0.767	0.364	0.387	0.265
Average	NA	NA	55 yrs	0.602	0.700	0.359	0.351	0.247

Scots pine sites tended to be younger averaging 54 years, and MSI values were also lower at an average of 0.571. Autocorrelation and AMS values for Scots pine ranked second highest out of the four shelterbelt species, at 0.688 and 0.367, respectively (Table 4.3). Despite the lower MSI value, Scots pine had the highest average R-squared value of 0.416, and an average cross-validated R-squared of 0.293 (Table 4.3).

Table 4.3 Site-specific location and chronology information for each Scots pine site, organized from south to north sites. Chron. Length = Chronology length, MSI = Mean series intercorrelation: measures strength of correlation between samples taken from the same site, based on 30 year overlapping sections, Auto Corr. = Auto correlation: measures effect of the previous year's growth on current year growth, AMS = average mean sensitivity: indicates the year-to-year variability in radial growth within the chronology, R-squared: measure of how much the variance in radial growth is explained by climate, Cross-Val R-squared: cross-validated R-squared: measures the predictive power of the model.

Scots Pine Site Name	**Latitude**	**Longitude**	**Chron. Length**	**MSI**	**Auto Corr.**	**AMS**	**R-Square**	**Cross-Val R-Squared**
17PLS00	50.120013°	-105.100752°	49 yrs. (1969-2017)	0.653	0.809	0.313	0.339	0.220
14SLS00	50.544306°	-103.607000°	71 yrs. (1943-2013)	0.577	0.529	0.364	0.367	0.263
18PLS00	50.555170˚	-108.772710˚	41 yrs. (1978-2018)	0.587	0.758	0.317	0.362	0.195
18ZLS00	50.977898˚	-104.951651˚	47 yrs. (1971-2017)	0.608	0.682	0.396	0.488	0.318
18CLS00	51.397566°	-102.889469°	41 yrs. (1978-2018)	0.500	0.777	0.301	0.354	0.267
14YLS00	51.419139°	-107.808000°	43 yrs. (1971-2013)	0.566	0.579	0.494	0.500	0.390
18XLS00	51.564583°	-109.309877	53 yrs (1966-2018)	0.607	0.425	0.425	0.494	0.409
11ILS00	52.124639°	-107.242472°	84 yrs. (1927-2010)	0.528	0.629	0.378	0.317	0.195
18WLS00	52.164887°	-109.429687°	53 yrs. (1966-2018)	0.613	0.827	0.463	0.485	0.303
13PLS00	52.385167°	-105.211889°	70 yrs. (1943-2012)	0.566	0.66	0.343	0.286	0.184
14BCLS00	52.407306°	-106.413250°	50 yrs. (1964-2013)	0.541	0.564	0.386	0.397	0.274
14PLS00	52.413344°	-107.252511°	44 yrs. (1970-2013)	0.520	0.830	0.337	0.475	0.368
11DLS00	52.915278°	-106.222028°	55 yrs. (1956-2010)	0.553	0.879	0.251	0.542	0.416
Average	NA	NA	54 yrs.	0.571	0.688	0.367	0.416	0.293

White spruce chronology lengths averaged 57 years, the oldest site being 89 years and the youngest 41 years. White spruce chronologies had the highest MSI and AMS values of the four shelterbelt species, averaging 0.689 and 0.39 respectively. The average autocorrelation value was 0.66 and ranked 3rd out of the four shelterbelt species (Table 4.4). White spruce R-squared values averaged 0.368 and when cross-validated averaged 0.266.

Table 4.4 Site-specific location and chronology information for each white spruce site, organized from south to north sites. Chron. Length = Chronology length, MSI = Mean series intercorrelation: measures strength of correlation between samples taken from the same site, based on 30 year overlapping sections, Auto Corr. = Auto correlation: measures effect of the previous year's growth on current year growth, AMS = average mean sensitivity: indicates the year-to-year variability in radial growth within the chronology, R-squared: measure of how much the variance in radial growth is explained by climate, Cross-Val R-squared: cross-validated R-squared: measures the predictive power of the model.

White Spruce Site Name	Latitude	Longitude	Chron. Length	MSI	Auto Corr.	AMS	R-Squared	Cross-val R-Squared
12AEL200	49.145	-104.300000	42 yrs. (1970-2011)	0.726	0.562	0.430	0.451	0.327
18VL200	49.49355	-105.991550	57 yrs. (1962-2018)	0.718	0.566	0.507	0.486	0.361
18KL200	49.71373	-101.685890	53 yrs. (1965-2017)	0.611	0.740	0.359	0.322	0.220
12ML200	49.83	-103.431000	66 yrs. (1946-2011)	0.712	0.786	0.374	0.392	0.311
18SL200	49.84461	-108.944760	48 yrs. (1971-2018)	0.583	0.665	0.289	0.404	0.334
17HL200	50.01675	-107.972790	45 yrs. (1973-2017)	0.622	0.600	0.292	0.376	0.267
12AAL200	50.079	-108.303000	61 yrs. (1952-2012)	0.718	0.675	0.488	0.333	0.233
12ACL200	50.36	-105.559000	50 yrs. (1963-2012)	0.524	0.409	0.397	0.339	0.215
11ANL200	50.44	-106.895000	89 yrs. (1922-2010)	0.788	0.611	0.449	0.323	0.244
12QL200	50.57	-104.063000	62 yrs. (1950-2011)	0.797	0.810	0.270	0.348	0.214
17DL200	50.59418	-105.887470	55 yrs. (1963-2017)	0.802	0.633	0.419	0.265	0.180
11ADL200	50.828278	-103.326944	64 yrs. (1947-2010)	0.800	0.718	0.457	0.440	0.336
12AHL200	50.92	-101.921000	43 yrs. (1970-2012)	0.638	0.790	0.327	0.266	0.139
12NL200	51.12489	-103.643000	59 yrs. (1953-2011)	0.761	0.817	0.300	0.376	0.257
12ANL200	51.212	-107.364000	52 yrs. (1960-2011)	0.653	0.667	0.524	0.391	0.314
15BL200	51.266833	-105.907800	50 yrs. (1965-2014)	0.668	0.472	0.498	0.403	0.328
12AIL200	51.618556	-102.075694	41 yrs. (1971-2011)	0.604	0.761	0.207	0.336	0.198
17CL200	51.70748	-108.587880	56 yrs. (1961-2016)	0.606	0.671	0.550	0.316	0.204
12OL200	51.7319	-103.844000	64 yrs. (1948-2011)	0.696	0.718	0.330	0.347	0.238
12GL200	51.961333	-103.794667	67 yrs. (1945-2011)	0.744	0.746	0.342	0.295	0.228
11JL200	52.077	-107.314000	67 yrs. (1945-2011)	0.802	0.528	0.458	0.400	0.320
11GL200	52.75	-108.099000	63 yrs. (1948-2010)	0.687	0.612	0.435	0.311	0.221
11DL200	52.915278	-106.222028	58 yrs. (1953-2010)	0.583	0.618	0.271	0.542	0.433
Average	NA	NA	57 yrs	0.689	0.660	0.390	0.368	0.266

4.2 Green ash

4.2.1 Relative importance of climate variables

Variability in green ash radial growth is largely explained by spring and summer precipitation and spring temperature. Current-June precipitation has the largest total sum of relative weights (Table 4.5), indicating that it has the greatest effect on green ash growth. Current-May precipitation and previous-June precipitation ranked as the second and third most important climate variables that affect green ash growth. Current-May temperature is considered the most important temperature variable affecting green ash growth and ranks as the fourth most important climate variable impacting green ash growth (Table 4.6).

Summer precipitation affects areas west of Saskatoon (between Saskatoon and Kindersley), south and west of Swift Current, and a small area east of Swift Current (Figure 4.1). Table 4.7 illustrates that June and July summer precipitation positively influences green ash growth, however, August precipitation appears to have a mostly negative influence across most sites. Spring precipitation positively affects areas around Prince Albert stretching south to Saskatoon and areas southeast of Saskatoon, and parts of southeastern Saskatchewan extending from Yorkton (Appendix Figure A.2) to south and west of Regina (Figure 4.1 and Table 4.7). The large area in the northeast corner of the raster that is mainly blue in maps 4.1b an 4.1g (Figure 4.1), does not have any green ash sites within it, and as a result the positive influence of summer precipitation and autumn temperature in this area may not be reflecting reality.

Autumn and winter precipitation have a small overall influence on green ash growth. Autumn precipitation positively influences green ash growth around Prince Albert stretching to Saskatoon and has a small influence in a central portion of Saskatchewan starting in Saskatoon and stretching to an area between Regina and Swift Current. Winter precipitation positively affects areas west of Prince Albert and an area around Swift Current (Figure 4.1 and Table 4.7).

Spring temperature negatively influences growth across the northern (Prince Albert area) and western (from Lloydminster south to the United States border) areas of the study area, and slightly affects areas northeast of Swift Current (Outlook area), north of Regina, and around

Estevan (Figure 4.1 and Table 4.8). Similarly, summer temperature negatively affects growth in the Outlook area and northern and western parts of the study area, but its area of influence is smaller. Summer temperature also has a small negative affect on areas south and west of Yorkton extending to south of Regina, and a small zone south of Swift Current (Appendix Figure A.2). Autumn (current-September and previous-October and November) and previous year's winter temperature have little influence on green ash growth. Autumn temperature has a small and mainly negative effect on green ash growth (Table 4.8) around Kindersley and Outlook stretching southwest towards Swift Current, and east and south of Prince Albert (Figure 4.1). Past winter temperature slightly and positively influences green ash growth around the Outlook and Swift Current areas extending south to the border (Figure 4.1 and Table 4.8).

Table 4.5 Green ash relative weights of precipitation climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Green ash sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Green ash Site Name	Previous Precipitation												Current Precipitation					
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Apr	May	Jun	Jul	Aug	Sep
12JLM00					40.1	30.8												10.3
12KLM00					30.1	29.1											13.4	
18TLM00				11.7										38.9	41.0		8.0	
18RLM00								20.3							23.9		18.7	
11AILM00														34.1	53.5			
18ILM00			18.2											48.4				
14BALM00						13.5						29.2	12.9	27.3				
18QLM00																		
11ALLM00									32.4				22.4	13.6				
12QLM00						41.1	17.8	5.2										
11AMLM00	22.5														7.1		41.4	
12AGLM00														24.5	38.2	22.5		
15BLM00										13.6					29.2			
18MLM00		10.6				16.5			14.9						36.2			
12PLM00					12.5	65.7	7.6	3.6										10.5
14ILM00															23.0	11.6	8.6	
13CLM00						15.0												
14XLM00								29.6						17.0	27.0			
13LLM00														29.4	23.8		8.2	
15DLM00											26.5		30.9	8.1	20.0	14.5		
14MLM00											20.8			46.4	18.6			
14BILM00					13.2										25.4			
14PLM00		21.7			21.2												57.1	
Total	22.5	32.3	18.2	11.7	117.0	211.7	25.5	58.7	47.2	13.6	47.3	29.2	66.2	287.8	366.8	48.6	155.3	20.8
Average	22.5	16.2	18.2	11.7	23.4	30.2	12.7	14.7	23.6	13.6	23.6	29.2	22.1	28.8	28.2	16.2	22.2	10.4

Table 4.6 Green ash relative weights of temperature climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Green ash sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Green ash	**Previous Temperature**												**Current Temperature**					
Site Name	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
12JLM00			18.9															
12KLM00				27.5														
18TLM00																		
18RLM00													27.5			9.6		
11AILM00																12.4		
18ILM00								12.0							21.4			
14BALM00	6.3				10.9													
18QLM00				17.4	9.3									73.2				
11ALLM00						17.4									14.2			
12QLM00					35.8													
11AMLM00					15.9				13.1									
12AGLM00								14.8										
15BLM00		10.9						6.3			24.6			15.4				
18MLM00								21.8										
12PLM00																		
14ILM00		10.6												29.4				
13CLM00			9.8	8.2				11.3						17.7	38.0			
14XLM00									26.5									
13LLM00													38.6					
15DLM00																		
14MLM00								14.2										
14BILM00									25.1					36.4				
14PLM00																		
Total	6.3	21.5	28.7	53.1	71.9	17.4	0.0	80.5	64.6	0.0	24.6	0.0	66.0	172.1	73.6	22.0	0.0	0.0
Average	6.3	10.8	14.3	17.7	18.0	17.4	0.0	13.4	21.5	0.0	24.6	0.0	33.0	34.4	24.5	11.0	0.0	0.0

Table 4.7 The precipitation climate variables and their model coefficients that are used in the future growth model for each green ash site across the southern half of Saskatchewan. The negative numbers show a negative correlation to the climate variable and positive numbers indicate a positive correlation to the climate variable. These climate variables combine previous and current year precipitation. Current year variables range from April-September and previous year range from January-December.

Green ash	**Spring Precip**			**Summer Precip**			**Autumn Precip**			**Winter Precip**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
15BLM00				0.004				0.005				
15DLM00		0.005	0.002	0.002	0.002				0.008			
18ILM00	0.003		0.003									
18TLM00		-0.003	0.002	0.003		-0.002						
12JLM00			0.004	0.003			0.002					
14XLM00			0.002	0.002		0.002						
14MLM00			0.003	0.001		-0.020			0.004			
12QLM00				0.003	0.002	-0.001						
11ALLM00		0.004	0.002				0.003					
14BALM00		0.003	0.002	-0.001						0.007		
14ILM00				0.002	0.001	-0.002						
18RLM00				0.001		-0.002						
13CLM00			0.002									
18MLM00				0.002			0.003				0.006	
14PLM00			-0.002			0.004					0.006	
11AILM00			0.003	0.002								
13LLM00			0.003	0.002		-0.001						
12AGLM00			0.003	0.003	0.002							
12KLM00			0.003	0.002		0.002						
12PLM00			0.002	0.003	0.001	-0.001	-0.002					
14BILM00			-0.002	0.001								
18QLM00												
11AMLM00				-0.001		0.003					0.006	

Table 4.8 The temperature climate variables and their model coefficients that are used in the future growth model for each green ash site across the southern half of Saskatchewan. The negative numbers show a negative correlation to the climate variable and the positive numbers indicate a positive correlation to the climate variable. These climate variables combine previous and current year temperature. Current year climate variables range from April-September and previous year range from January-December.

Green ash	**Spring Temp**			**Summer Temp**			**Autumn Temp**			**Winter Temp**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
15BLM00						-0.027			-0.043			0.020
15DLM00												
18ILM00				-0.033		-0.020						
18TLM00												
12JLM00	-0.025											
14XLM00							-0.025					
14MLM00						-0.020						
12QLM00			-0.048									
11ALLM00				-0.036								
14BALM00			0.017							-0.009		
14ILM00			-0.035			-0.026						0.011
18RLM00		-0.019			-0.019							
13CLM00				-0.059								-0.022
18MLM00						-0.031						
14PLM00												
11AILM00			-0.024									
13LLM00		-0.027										
12AGLM00						-0.024						
12KLM00		-0.028										
12PLM00												
14BILM00			-0.034				-0.025					
18QLM00			-0.034	-0.030				0.031				
11AMLM00			0.025				0.014					

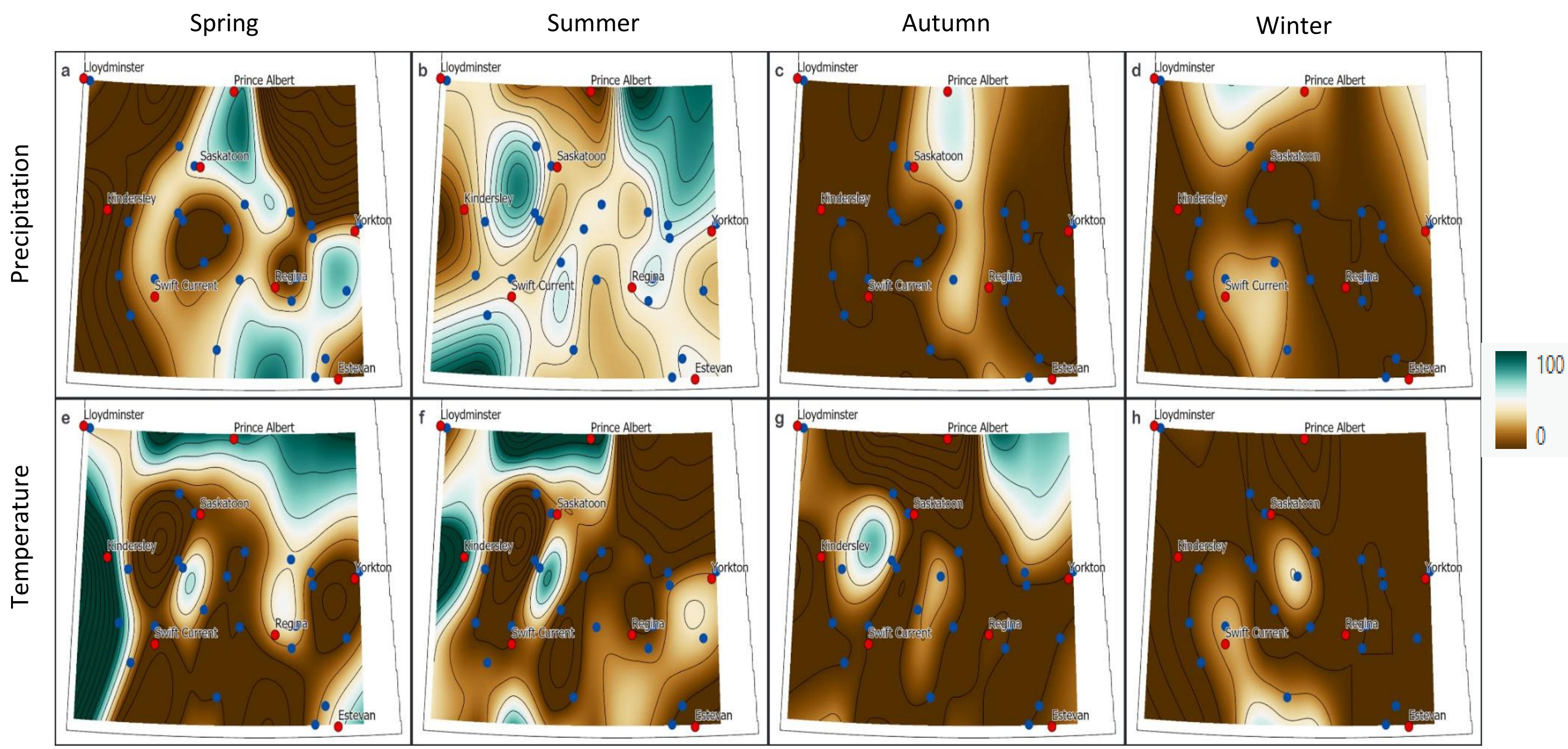

Figure 4.1 Mapped relative weights of precipitation and temperature variables used in green ash future growth models. The blue areas show sites that are influenced by a climate variable and the brown areas are not influenced by the climate variable. The contour lines show the increasing or decreasing of value in increments of 20%. The blue dots represent green ash sites. Current and previous climate variables are grouped together. Spring=MAM, May; Summer=JJA; Autumn=SON; Winter=DJF. Relative weights approximate in percent (scale of 0-100%), how much each climate variable contributes to the R-squared (total variance of tree-growth explained by climate).

4.2.2 Predicted Future Growth

The overall trend of green ash radial growth across all models and RCPs in Figures 4.2 and 4.3 suggests that a large swath through the center of Saskatchewan will experience slight increases in growth, excluding areas surrounding Outlook and Regina. The rest of the province is predicted to experience decreases in green ash growth, except for the northeast corner of the study area (east of Prince Albert), which is predicted to experience increases in growth under the ACCESS1-0 and CNRM-CM5 models. The extreme northeast corner of the study area may not be accurate since there are no green ash sites in the area. CanESM2 and INMCM4 show more extreme increases and decreases in predicted green ash growth than ACCESS1-0 and CNRM-CM5 models do (Figures 4.2 and 4.3). Yet, CanESM2 and INMCM4 have lower probabilities that growth will change in the future under RCP 4.5 (Table 4.9), and ACCESS1-0 and CNRM-CM5 show a high probability that green ash future growth will change from past growth in both RCP 4.5 and 8.5(p-values below 0.05 in Table 4.9). Under RCP 8.5, the CanESM2 model shows a higher probability of changes in future green ash growth, especially in the years from 2075-2100 (p-values below 0.05), whereas in the model INMCM4, there is predicted to be no significant difference between past and future green ash growth throughout most years, regardless of the RCP (Table 4.9).CanESM2 and INMCM4 models predict that green ash just west of Yorkton will experience increases in growth, and ACCESS1-0 and CNRM-CM5 models predict green ash growth will decrease in the area (Figures 4.2 and 4.3). RCP 8.5 illustrates more dramatic changes in green ash growth than RCP 4.5 (Figures 4.2 and 4.3).

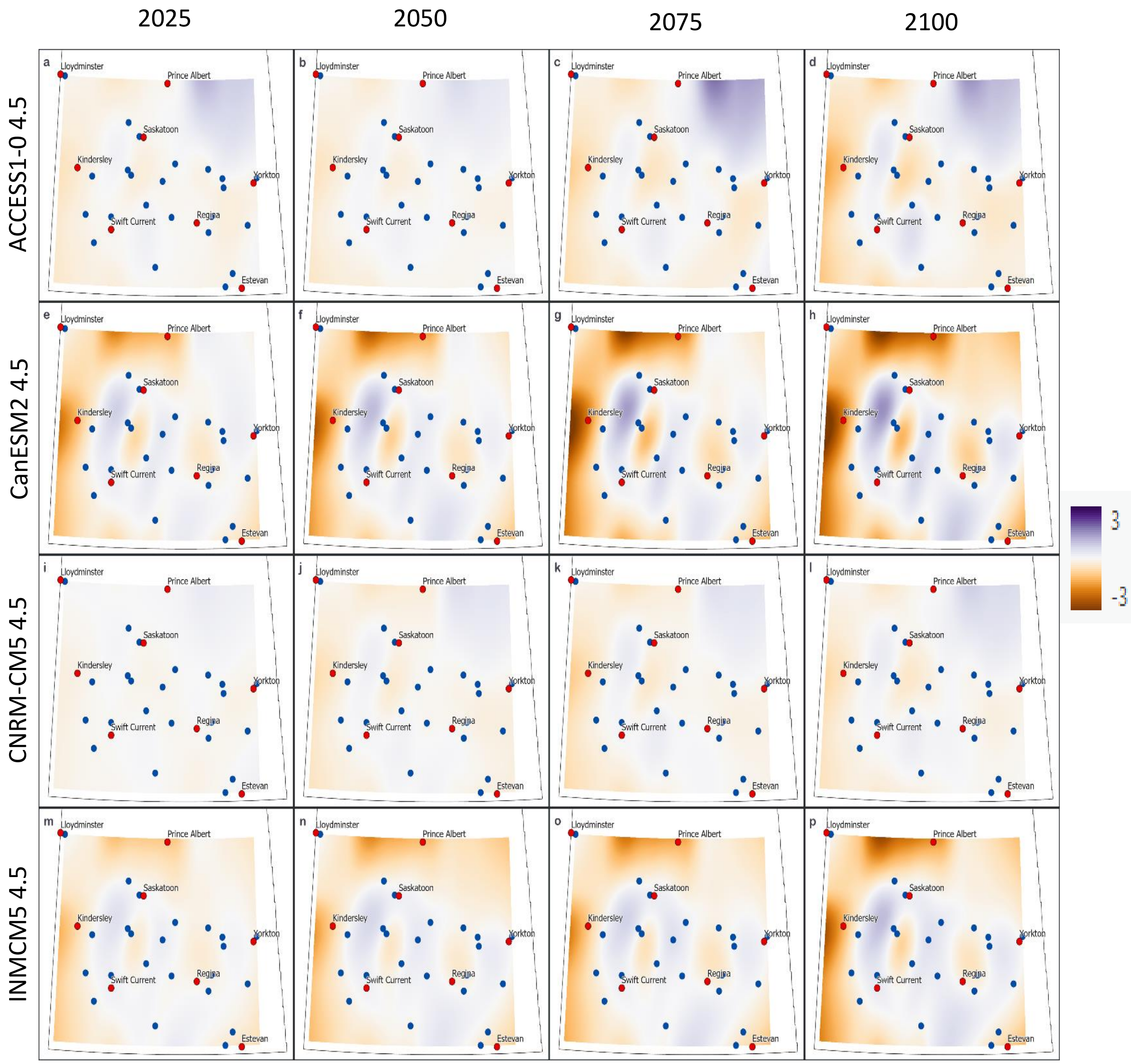

Figure 4.2 Mapped difference between past growth and predicted future green ash growth up to the year 2100 for four different climate models at the RCP 4.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

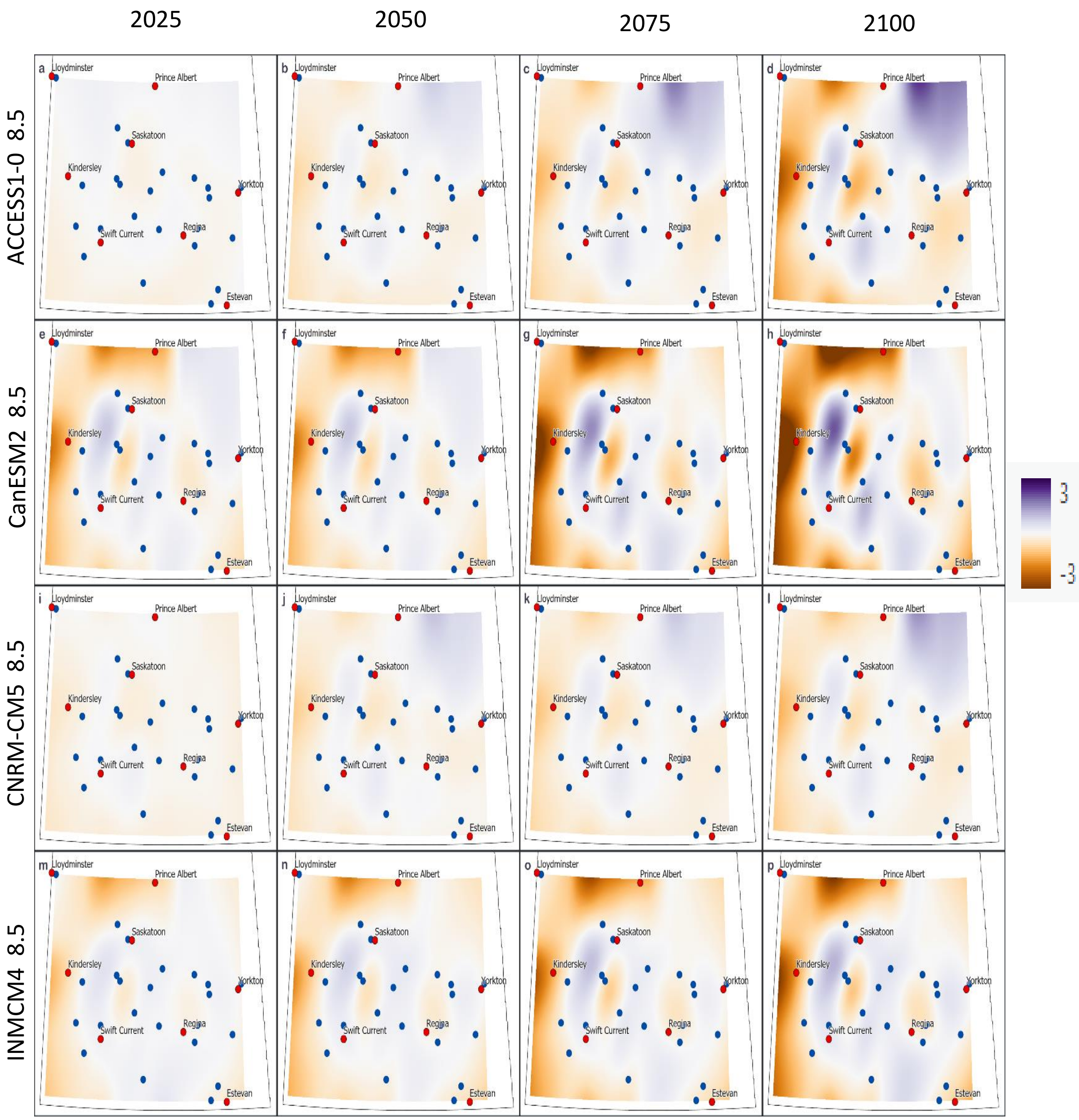

Figure 4.3 Mapped difference between past growth and predicted future green ash growth up to the year 2100 for four different climate models at the RCP 8.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

Table 4.9 Probability that there is a difference between past and future green ash growth for the specific model, RCP, and 25-year time increment into the future. The lower the p-values, the higher probability that there is a difference between past and future growth.

Global Climate Models for RCP 4.5 and 8.5	Green ash p-values			
	Year			
	2025	2050	2075	2100
ACCESS1-0 4.5	0.0000002	0.0000415	0.0000123	0.0000127
CanESM2 4.5	0.0554817	0.1000000	0.0298838	0.0778882
CNRM-CM5 4.5	0.0000091	0.0000046	0.0000237	0.0000915
INMCM4 4.5	0.0251323	0.3725609	0.2606538	0.4947383
ACCESS1-0 8.5	0.0000045	0.0000014	0.0007342	0.0000689
CanESM2 8.5	0.0624657	0.0754609	0.0289496	0.0080782
CNRM-CM5 8.5	0.0000003	0.0000148	0.0000047	0.0001876
INMCM4 8.5	0.6510625	0.2186759	0.0655801	0.3690394

Since green ash growth is highly influenced by the months of May and June, the predicted changes in green ash growth seen in Figures 4.4 and 4.5 are mainly affected by the forecasted changes in May and June under climate change models. The predicted future increase in green ash radial growth matches the spring precipitation relative weights pattern as seen in Figure 4.4. This projected increase can therefore be attributed to the predicted increase in spring precipitation under future models (Figures 2.3 and 2.5), since green ash growth is positively correlated to spring precipitation (Table 4.7). The models ACCESS1-0 and CNRM-CM5 appear to be positively influenced by summer precipitation in the northeast corner of the raster (north and west of Yorkton, Figure 4.4c, 4.4e). Figures 2.2 and 2.4 predict that summer precipitation will decrease under climate change, but these maps group all of the summer months together (JJA) to take an average. The most influential climate variable, June precipitation, which is considered a summer month is predicted to slightly increase under the RCP 4.5 for the models ACCESS1-0 and CNRM-CM5 (Figure 4.6). Whereas July and August precipitation are predicted to decrease, which accounts for the general trend of decreasing summer precipitation seen in Figures 2.3 and 2.5. This slight increase in June precipitation likely accounts for the predicted positive change in green ash growth in the northeast corner of the raster, since green ash growth is positively related to June precipitation (Table 4.7). However, there are no green ash sites in this area, meaning that this information should be interpreted with caution, although it does indicate that the optimum climate for green ash will be present in this area in the future Summer (mainly June) precipitation also highly influences the areas west of Saskatoon, and south of Swift Current, but there are no increases in green ash growth predicted in these areas. This is likely because spring and summer temperature also affect these areas and have a greater negative impact than summer (June) precipitation. The predicted rise in spring and summer temperatures are negatively correlated with green ash growth, which explains why the areas where spring and summer temperature have the highest influence match the pattern of decreasing green ash growth in the models CanESM2 and INMCM4 under RCP 4.5 (Figure 4.5). RCP 8.5 forces greater increases in spring precipitation and temperature and summer temperature (Figures 2.4 and 2.5), which results in greater increases and decreases in growth in the pattern discussed above (Figures 4.2 and 4.3). Only models CanESM2 and INMCM4 were shown in Figure 4.5, because the negative effect that spring and summer temperature has on green ash growth is very clear, whereas this pattern is not as clearly seen in ACCESS1-0 and CNRM-CM5.

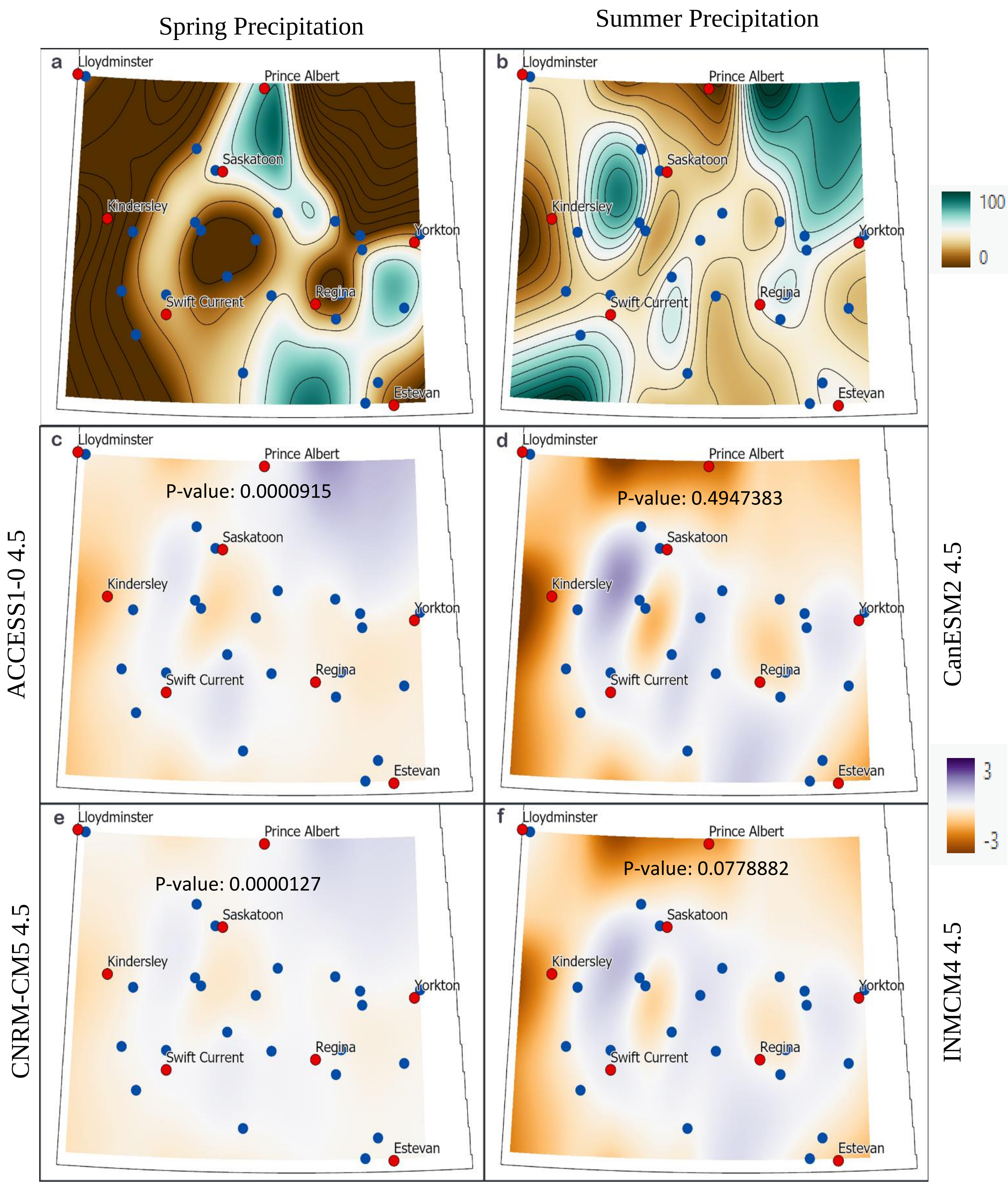

Figure 4.4 Spring and summer precipitation relative weights maps identify areas where spring and summer precipitation have the highest influence on green ash growth in the southern half of Saskatchewan (maps a and b), compared to maps that predict changes in green ash growth for four climate models under the RCP 4.5 in the year 2100 (maps c, d, e, f).

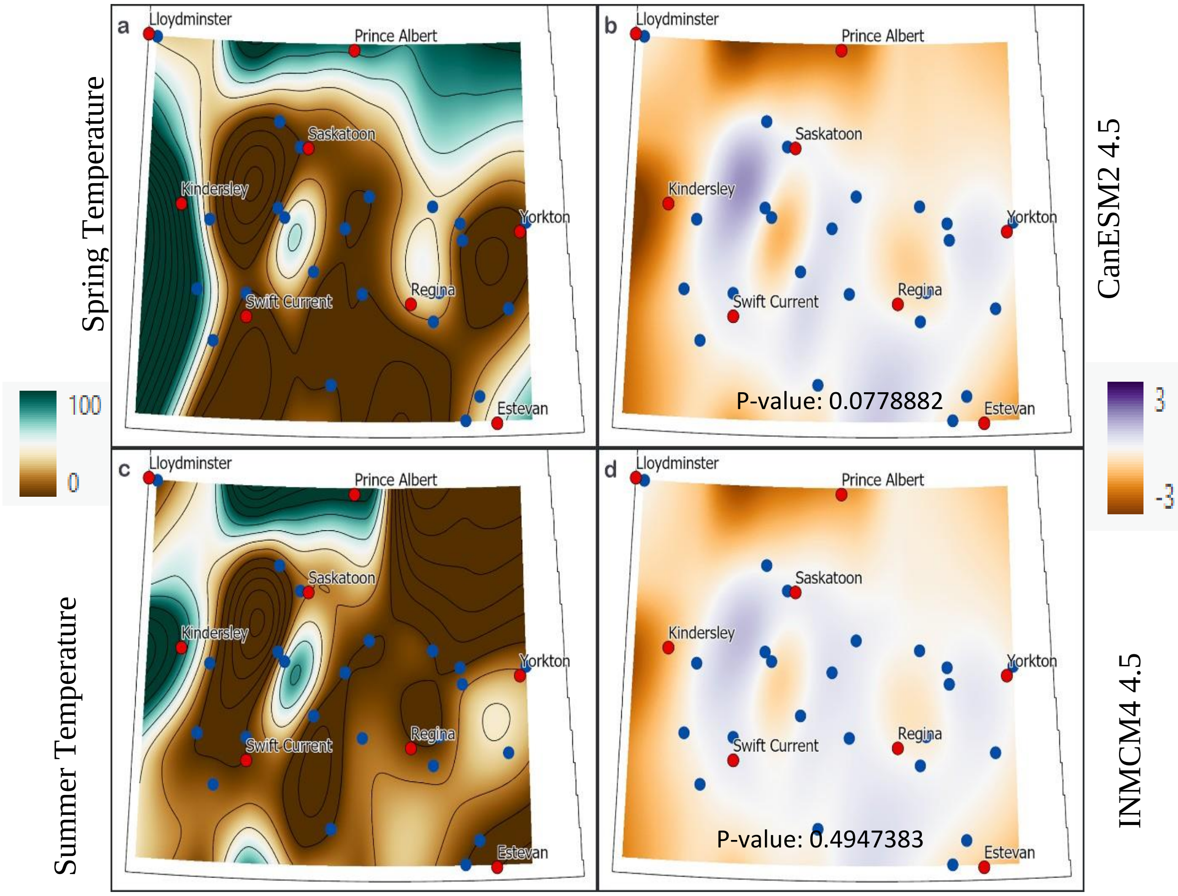

Figure 4.5 Maps showing the areas where spring and summer temperature have the highest influence on green ash radial growth (maps a and c), compared to the predicted changes in green ash growth for climate models CanESM2 and INMCM4 under the RCP 4.5 (maps b and d) in the southern half of Saskatchewan. P-values display the probability that future growth will be different from past growth.

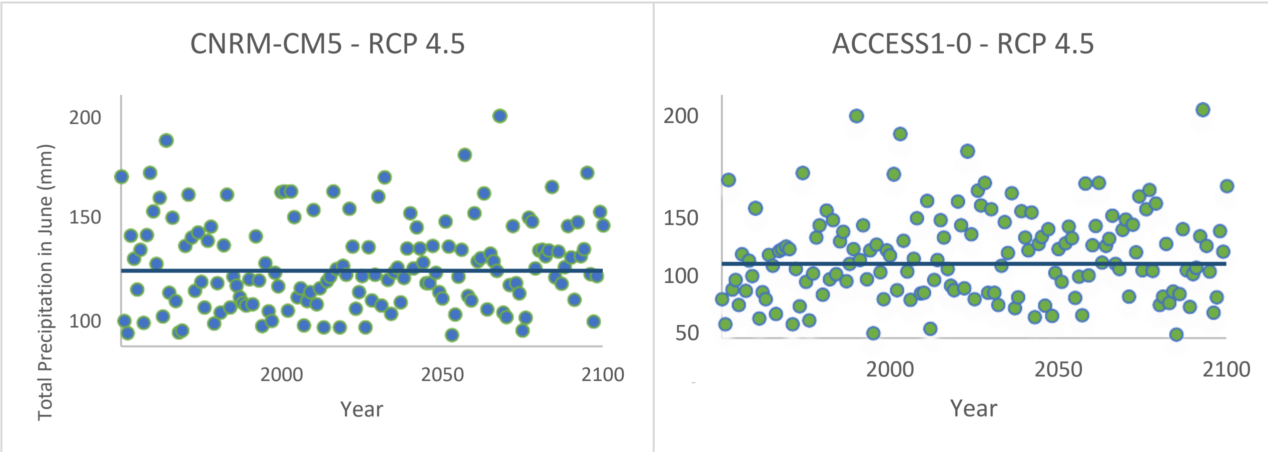

Figure 4.6 Trends in total precipitation (mm) in June from 1950 to 2100 for the climate models CNRM-CM5 and ACCESS1-0 under the RCP 4.5. This data was taken from the 10 km grid square located near the northeast corner of the raster (Figure 3.1) at 51.542˚, -103.54˚.

4.3 Hybrid Poplar

4.3.1 Relative Weights

Previous August temperature has the largest effect on hybrid poplar radial growth, followed by current May temperature, current June precipitation, and current June temperature (Table 4.10 and 4.11). The relative importance of climate variables on hybrid poplar growth appears to be highly site specific since the total relative weights for the precipitation climate variables are similar in weight to each other (Table 4.10). Fewer sites were collected for hybrid poplar, and as a result the relative weights and predicted growth rasters did not cover the entire study area (three southernmost soil zones in Saskatchewan). Prince Albert, Lloydminster, Yorkton, and Estevan are some of the cities where the raster does not cover. The Regina area has no hybrid poplar sites, indicating that the influence of spring and winter precipitation were interpolated in this area based on nearby sites, and therefore this area may not be accurate since there are no hybrid poplar sites representative of the area (Figure 4.7).

Hybrid poplar is affected by both autumn precipitation and summer temperature in the area west of Saskatoon extending towards Kindersley (Figure 4.7). According Tables 4.12 and 4.13, autumn precipitation has a positive influence on growth and summer temperature has a negative influence. Summer and spring temperature negatively influence hybrid poplar growth in an area east of Saskatoon (Table 4.13 and Figure 4.7). Spring temperature positively influences the area around Saskatoon extending south and eastwards (Figure 4.7 and Table 4.13). Summer precipitation is positively correlated to hybrid poplar growth in areas north of Saskatoon and west of Swift Current.

Table 4.10. Hybrid poplar relative weights of precipitation climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Hybrid poplar sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Hybrid poplar Site Name	**Previous Precipitation**												**Current Precipitation**					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
14BBLN00	15.8								13.1						42.4			
14KLN00			18.7			21.2		33.8										
18YLN00												26.5	27.7					
11MLN00									39.1	15.3								
13ILN00														29.7				
14HLN00											25.2	21.4				12.4		
14BDLN00							31.8							30.9				
14BELN00																	16.5	
18DLN00													21.1		31.6	21.8		
Total	15.8	0.0	18.7	0.0	0.0	21.2	31.8	33.8	52.2	15.3	25.2	47.9	48.8	60.5	74.0	34.2	16.5	0.0
Average	15.8	0.0	18.7	0.0	0.0	21.2	31.8	33.8	26.1	15.3	25.2	24.0	24.4	30.3	37.0	17.1	16.5	0.0

Table 4.11 Hybrid poplar relative weights of temperature climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Hybrid poplar sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Hybrid poplar Site Name	**Previous Temperature**												**Current Temperature**					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
14BBLN00														11.8				17.0
14KLN00															26.3			
18YLN00	18.8															26.9		
11MLN00								19.8								25.8		
13ILN00				10.6	11.0			48.7										
14HLN00															41.0			
14BDLN00		14.0		9.3	14.1													
14BELN00								38.0						45.5				
18DLN00														25.5				
Total	18.8	14.0	0.0	10.0	12.6	0.0	0.0	106.5	0.0	0.0	0.0	0.0	0.0	82.8	67.3	52.7	0.0	17.0
Average	18.8	14.0	0.0	10.0	12.6	0.0	0.0	35.5	0.0	0.0	0.0	0.0	0.0	27.6	33.7	26.3	0.0	17.0

Table 4.12 The precipitation climate variables and their model coefficients that are used in the future growth model for each hybrid poplar site across the southern half of Saskatchewan. Negative numbers show a negative correlation to the climate variable and positive numbers indicate a positive correlation to the climate variable. These climate variables combine previous and current year precipitation. Current year climate variables range from April-September and previous year range from January-December.

Hybrid poplar	**Spring Precip**			**Summer Precip**			**Autumn Precip**			**Winter Precip**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
18DLN00		0.003		0.003	0.002							
14BDLN00			0.005		0.004							
14BELN00						-0.001						
14BBLN00				0.002			0.001				0.004	
11MLN00							0.004	0.003				
14KLN00	-0.005			-0.002		0.002						
14HLN00					0.003					0.009		
18YLN00		0.004								0.005		
13ILN00			0.002									

Table 4.13 The temperature climate variables and their model coefficients that are used in the future growth model for each hybrid poplar site across the southern half of Saskatchewan. Negative numbers show a negative correlation to the climate variable and positive numbers indicate a positive correlation to the climate variable. These climate variables combine previous and current year temperature. Current year climate variables range from April-September and previous year range from January-December.

Hybrid poplar	**Spring Temp**			**Summer Temp**			**Autumn Temp**			**Winter Temp**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
18DLN00			-0.034									
14BDLN00		0.043	-0.061									-0.034
14BELN00			-0.035			-0.027						
14BBLN00			0.020				0.016					
11MLN00					-0.051	-0.034						
14KLN00				-0.030								
14HLN00				-0.076					-0.034			
18YLN00					-0.045						-0.011	
13ILN00		0.001	-0.021			-0.035						

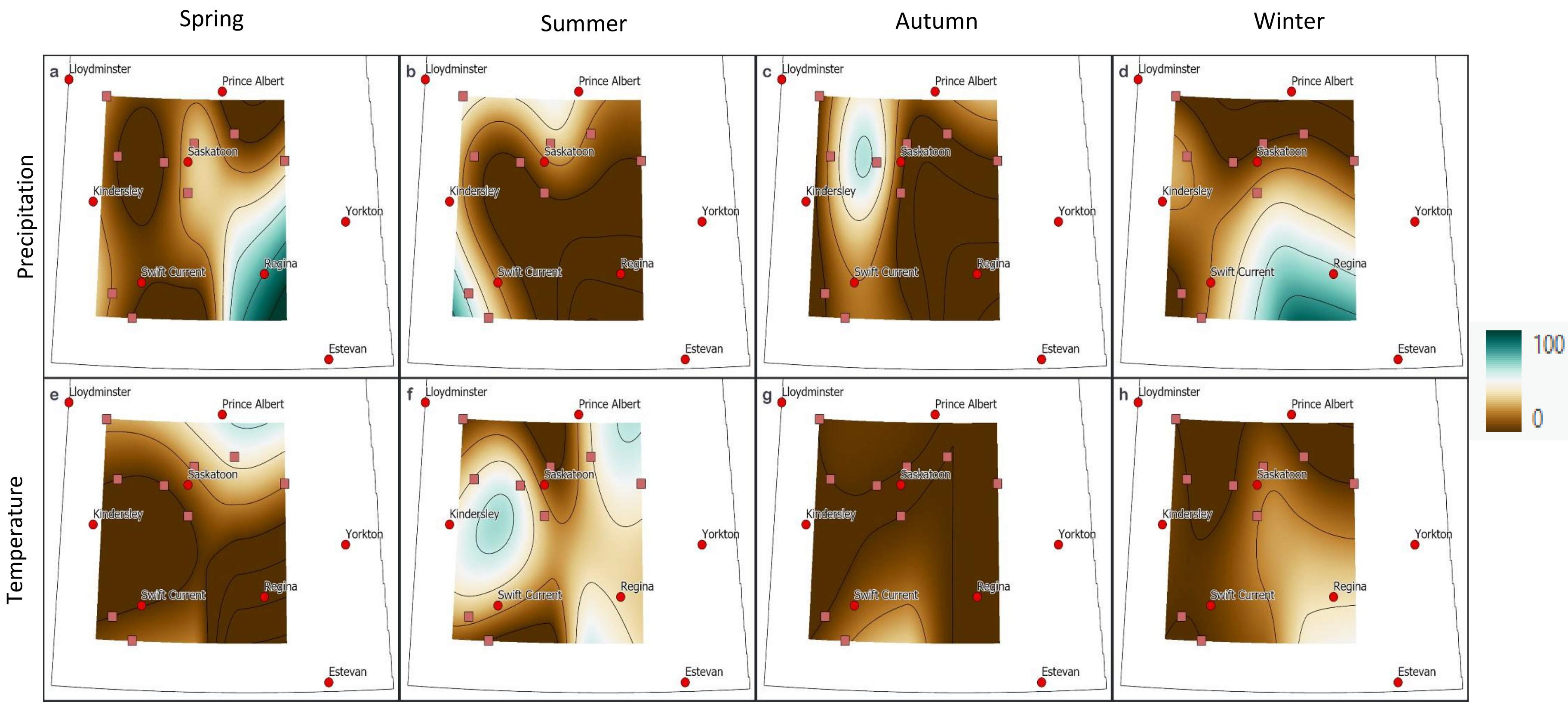

Figure 4.7 Mapped relative weights of precipitation and temperature variables used in hybrid poplar future growth models. The blue areas show sites that are influenced by a climate variable and the brown areas are not influenced by the climate variable. The contour lines show the increasing or decreasing of value in increments of 20%. Current and previous climate variables are grouped together. Spring=MAM; Summer=JJA; Autumn=SON; Winter=DJF. Pink squares represent hybrid poplar sites. Relative weights approximate in percent (scale of 0-100%), how much each climate variable contributes to the R-squared (total variance of tree-growth explained by climate).

4.3.2 Predicted Future Growth

Across all climate models and RCPs, hybrid poplar is predicted to experience a slight decrease in growth across most of the southern half of Saskatchewan (Figures 4.8 and 4.9). The lower p-values for ACCESS1-0, CanESM2, and CNRM-CM5 indicate that there is a high probability that changes in growth will occur (Table 4.14). However, for the model INMCM4, there is a lower probability that changes in hybrid poplar growth will occur, since p-values are higher and often above the significance level of 0.05 (Table 4.14). ACCESS1-0, CanESM2, and CNRM-CM5 models predict some slight increases or no change in growth around the Swift Current area, and the CanESM2 and INMCM4 model shows slight increases in hybrid poplar growth east of Saskatoon (Figures 4.8 and 4.9). For both RCP 4.5 and 8.5, the models show a gradual shift to greater decreases in hybrid poplar growth into the future and increases in growth around the Swift Current area (Figures 4.8 and 4.9). The INMCM4 model under RCP 4.5 and 8.5 predicts the least amount of changes in hybrid poplar growth, which is also supported by the lower probability of changes in growth seen in Table 4.14. The west half of the INMCM4 raster predicts that hybrid poplar will experience gradual slight decreases in growth, and the east half of the raster predicts slight increases in radial growth further into the future. However, it is important to keep in mind that hybrid poplar has few sites, and the interpolated areas far from hybrid sites should be interpreted with caution.

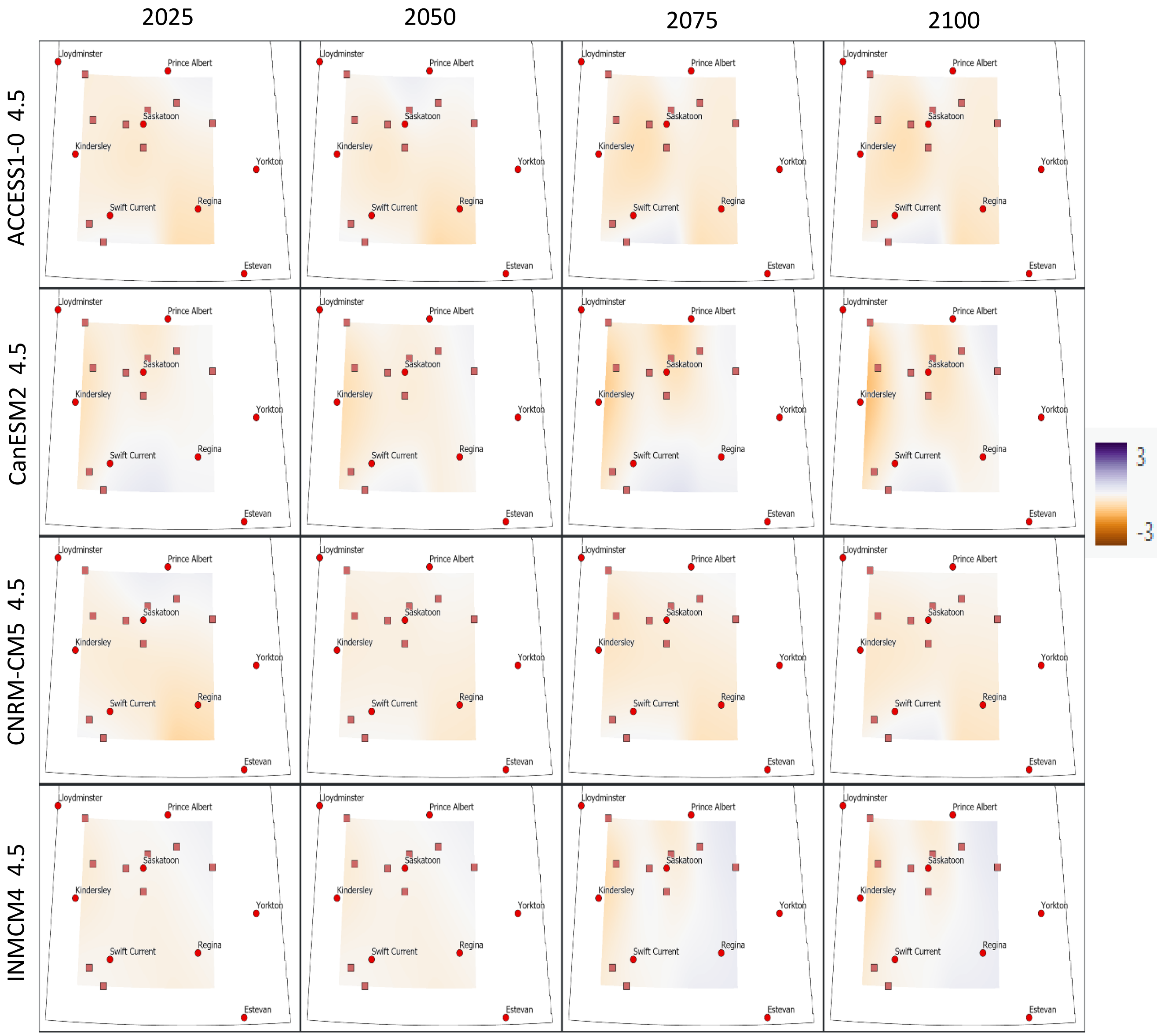

Figure 4.8 Mapped difference between past growth and predicted future growth until 2100 for hybrid poplar for four different climate models at the RCP 4.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

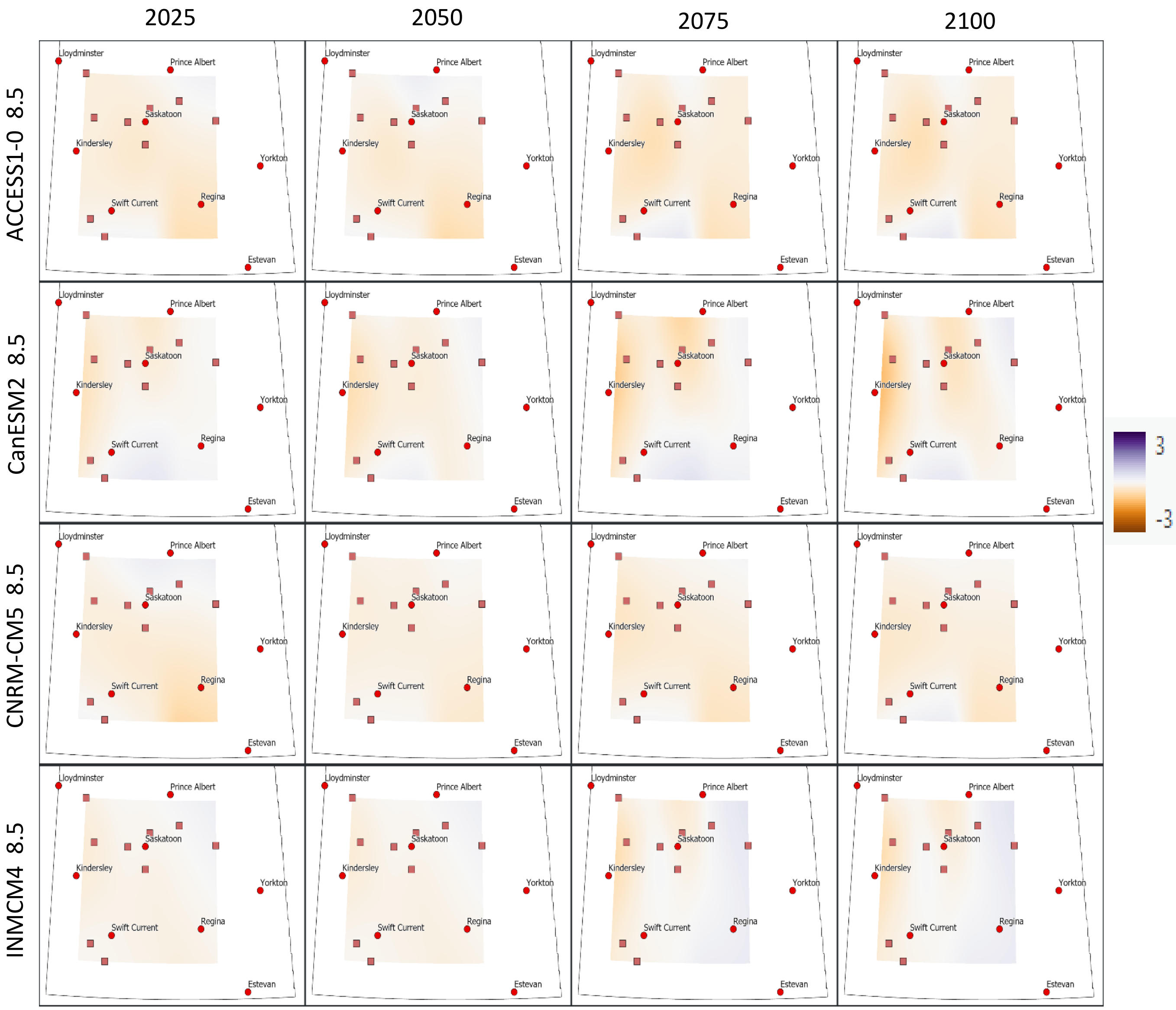

Figure 4.9 Mapped difference between past growth and predicted future growth until 2100 for hybrid poplar for four different climate models at the RCP 8.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

Table 4.14 Probability that there is a difference between past and future hybrid poplar growth for the specific model, RCP, and 25-year time increment into the future. The lower the p-values, the higher the chance that there is a difference.

Global Climate Models for RCP 4.5 and 8.5	Hybrid poplar p-values			
	Year			
	2025	2050	2075	2100
ACCESS1-0 4.5	0.0025849	0.0090925	0.0041932	0.0022191
CanESM2 4.5	0.0055119	0.0067789	0.0068979	0.0226612
CNRM-CM5 4.5	0.0177772	0.0001057	0.0020996	0.0028957
INMCM5 4.5	0.0367596	0.1509101	0.0995481	0.1436882
ACCESS1-0 8.5	0.0060268	0.0009172	0.0077964	0.0021116
CanESM2 8.5	0.0027394	0.0074649	0.0080566	0.0045102
CNRM-CM5 8.5	0.0068761	0.0006167	0.0016413	0.0028979
INMCM5 8.5	0.0664028	0.1041140	0.0458452	0.0595311

Decreases in hybrid poplar growth can be mainly attributed to predicted increases in summer temperature (Figures 2.2 and 2.4), since summer temperatures are negatively correlated to hybrid poplar growth (Table 4.13). The relative weights map (Figure 4.7) show that summer temperature affects hybrid poplar growth across most of the study area, except for the Saskatoon and Swift Current areas. As a result, hybrid poplar radial growth in the Swift Current area is predicted to increase since summer temperature is not considered to largely affect this area. This predicted increase is based off one site (14BBLN00) (site map Figure 3.1). At this site, hybrid poplar growth is positively related to spring and autumn temperatures that are predicted to increase, and autumn and winter precipitation that are also predicted to increase (Tables 4.12 and 4.13 and Figures 2.2, 2.3, 2.4, 2.5). The positive correlation to spring and autumn temperatures could be explained by the maintenance of the shelterbelts by the landowners (Rempel, 2014), or could be a positive response of hybrid poplar to an expanding growing season (Seserman et al., 2018). Maps under the RCP 8.5 in the year 2100 were used for Figure 4.6 because they showed the most distinct pattern in predicted decreases and increases in hybrid growth across the study area. The predicted changes in growth maps under RCP 4.5 show very slight decreases in hybrid poplar growth and it is difficult to see a pattern. Decreases in hybrid poplar radial growth are slow and small because the positive effect that autumn precipitation has on hybrid poplar growth, counteracts the negative effects of higher summer temperatures (Figure 4.10).

The reason the INMCM4 climate model shows less of a decrease in hybrid poplar growth is because it predicts less of an increase in summer temperatures (Clutz, 2020). The increases in hybrid poplar growth in the eastern half of the study area could likely be attributed to the positive effect that spring and winter precipitation have in the area (Figure 4.7). Overall, the slight changes in hybrid poplar are mainly caused by the negative effect of rising summer temperatures counteracted by the positive impact of autumn precipitation.

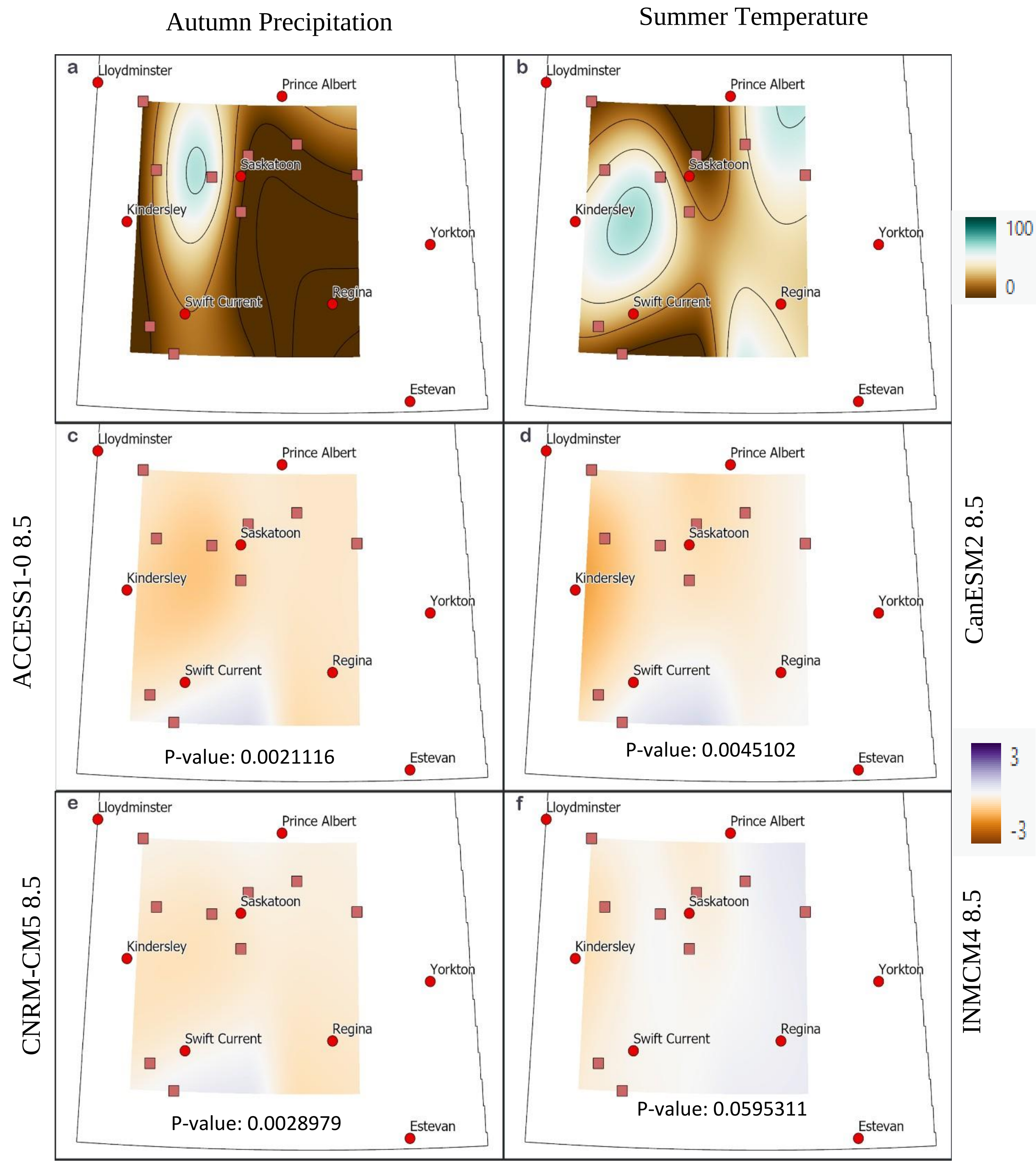

Figure 4.10 Autumn precipitation (current September and previous SON) and summer temperature relative weights maps that identify areas where these climate variables have the highest influence in the southern half of Saskatchewan (maps a and b), compared to maps that predict changes in hybrid growth for four climate models under the RCP 8.5 in the year 2100 (maps c, d, e, f). P-values display the probability that future growth will be different from past growth.

4.4 Scots Pine

4.4.1 Relative Weights

The Swift Current area is positively influenced by spring and summer precipitation (Figure 4.11 and Table 4.15). Summer precipitation also positively affects what appears to be most of the Dark Brown soil zone region (from Regina extending northwest through Saskatoon to Lloydminster). Autumn precipitation and autumn temperature have a small but positive affect around Saskatoon (Figure 4.11 and Tables 4.15 and 4.16). Spring temperature has a positive influence on areas southeast of Prince Albert extending towards Yorkton and southwest of Prince Albert.

Scots pine site locations did not cover the entire study area. The southern, eastern, and northernmost parts of the study area were not covered by the raster. Current June precipitation has the largest total sum of relative weights for Scots pine and the highest average relative weight, indicating that it has the largest effect on Scots pine radial growth (Tables 4.17 and 4.18). The second greatest influence on Scots pine growth is previous August temperature, followed by current May precipitation and previous June precipitation (Tables 4.17 and 4.18).

Table 4.15 The precipitation climate variables and their model coefficients that are used in the future growth model for each Scots pine site across the southern half of Saskatchewan. Negative numbers show a negative correlation to climate variables and positive numbers indicate a positive correlation to climate variables. These climate variables combine previous and current year precipitation. Current year climate variables range from April-September and previous year range from January-December.

Scots pine	**Spring Precip**			**Summer Precip**			**Autumn Precip**			**Winter Precip**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
11DLS00			-0.002				0.002					
11ILS00					0.001		0.003	0.002				
18CLS00			-0.002									
13PLS00												
14SLS00			0.002	0.002								
14PLS00				0.003								
14YLS00			0.004					0.005				-0.008
17PLS00	0.004											
18ZLS00				-0.006						0.008	0.008	
18PLS00					0.003			0.008				
18WLS00				0.003			0.003					
14BCLS00			0.003	0.003								
18XLS00			0.002	0.002					0.007			

Table 4.16 The temperature climate variables and their model coefficients that are used in the future growth model for each Scots pine site across the southern half of Saskatchewan. Positive numbers show a negative correlation to climate variables and positive numbers indicate a positive correlation to climate variables. These climate variables combine previous and current year temperature. Current year climate variables range from April-September and previous year range from January-December.

Scots pine	**Spring Temp**			**Summer Temp**			**Autumn Temp**			**Winter Temp**		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
11DLS00		0.019				-0.026	0.017					-0.010
11ILS00						-0.026		0.022				
18CLS00		0.021										-0.012
13PLS00			0.029	-0.040		-0.018		0.011				
14SLS00							-0.019	0.011				
14PLS00			0.044	0.037			-0.027					
14YLS00						-0.025						
17PLS00							-0.047	0.025			-0.018	
18ZLS00				-0.059								
18PLS00						-0.040						
18WLS00	-0.029	-0.028			-0.060	-0.033						
14BCLS00										0.017		
18XLS00					-0.060	-0.040						

Table 4.17 Scots pine relative weights of precipitation climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Scots pine sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Scots Pine	Previous Precipitation												Current Precipitation					
Site Name	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Apr	May	Jun	Jul	Aug	Sep
17PLS00													22.8					
14SLS00														23.2	58.1			
18PLS00						38.0				9.9						23.0		
18ZLS00	7.8					51.4						27.7						
18CLS00					37.7													
14YLS00		14.4								19.7				53.9				
18XLS00											22.7			16.1	15.2			
11ILS00							5.8		28.9	11.8								
18WLS00															29.3			5.7
13PLS00																		
14BCLS00														33.4	45.6			
14PLS00															44.4			
11DLS00					13.6				9.9									
Total	7.8	14.4	0.0	0.0	51.3	89.4	5.8	0.0	38.8	41.3	22.7	27.7	22.8	126.7	192.5	23.0	0.0	5.7
Average	7.8	14.4	0.0	0.0	25.7	44.7	5.9	0.0	19.4	13.8	22.7	27.7	22.8	31.7	38.5	23.0	0.0	5.7

Table 4.18. Scots pine relative weights of temperature climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. Scots pine sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

Scots Pine	Previous Temperature												Current Temperature					
Site Name	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Apr	May	Jun	Jul	Aug	Sep
17PLS00	31.8								32.5		12.9							
14SLS00									9.9		8.8							
18PLS00								29.2										
18ZLS00															13.1			
18CLS00		23.4											38.9					
14YLS00								12.0										
18XLS00								21.9								24.1		
11ILS00								21.5			31.9							
18WLS00			24.7					13.7					10.2			16.4		
13PLS00								24.6			14.8			28.2	32.4			
14BCLS00												20.9						
14PLS00						18.6								19.3				17.7
11DLS00		8.4						26.1					24.9					17.0
Total	31.8	31.8	24.7	0.0	0.0	18.6	0.0	149.1	42.3	0.0	68.5	20.9	74.1	47.5	45.5	40.6	0.0	34.7
Average	31.8	15.9	24.7	0.0	0.0	18.6	0.0	21.3	21.2	0.0	17.1	20.9	24.7	23.8	22.7	20.3	0.0	17.3

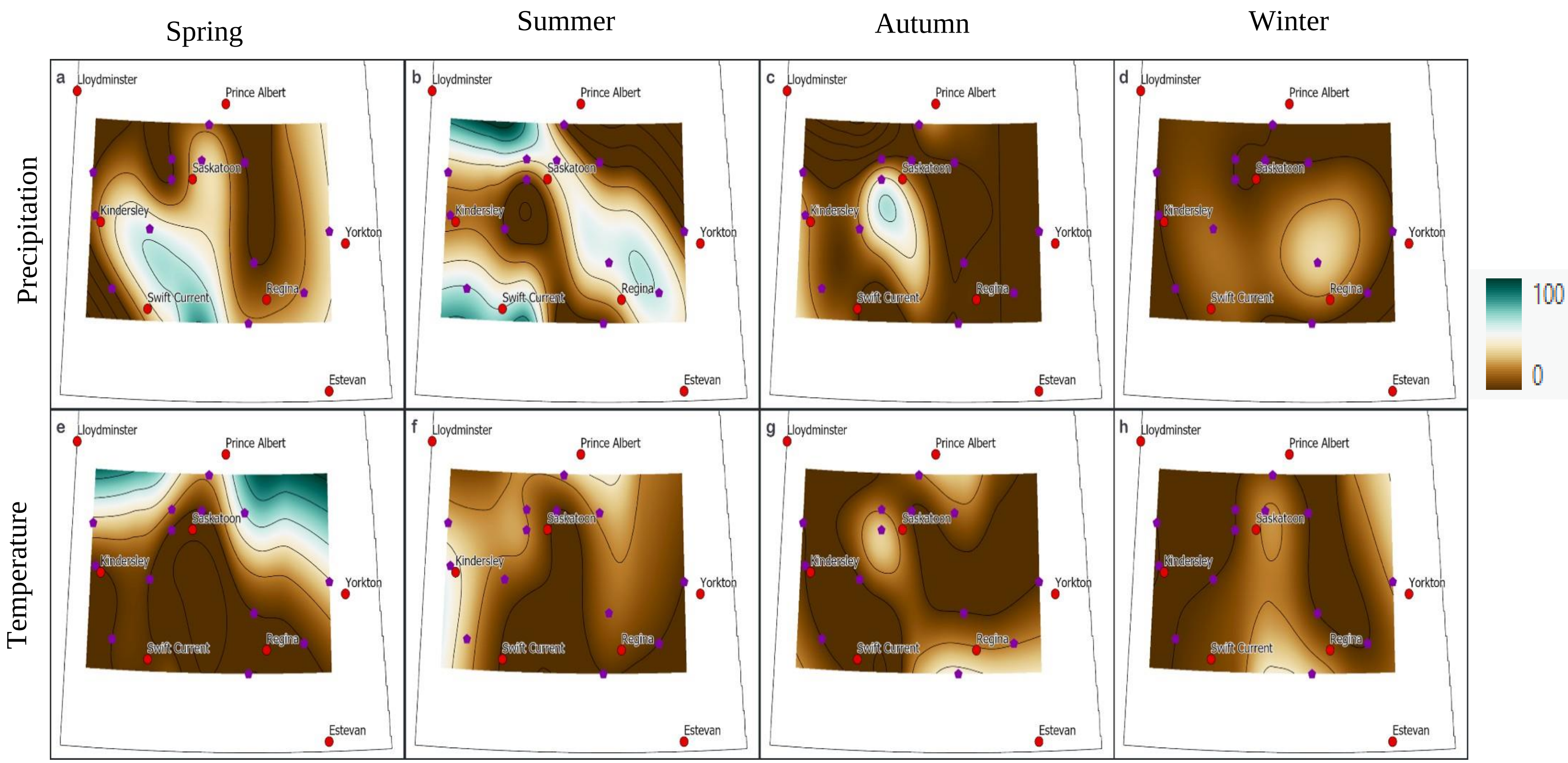

Figure 4.11 Mapped relative weights of precipitation and temperature variables used in Scots pine future growth models. The blue areas show sites that are influenced by a climate variable and the brown areas are not influenced by the climate variable. The contour lines show the increasing or decreasing of value in increments of 20%. Current and previous climate variables are grouped together. Spring=MAM; Summer=JJA; Autumn=SAN; Winter=DJF. Relative weights approximate in percent (scale of 0-100%), how much each climate variable contributes to the R-squared (total variance of tree-growth explained by climate).

4.4.2 Predicting Future Growth

Forecasted changes in Scots pine growth show many differences between models. For RCP 4.5, the ACCESS1-0 model predicts slight decreases in Scots pine future growth for most of the southern half of Saskatchewan, except for regions south of Swift Current, east in the Yorkton area, and northwest of Saskatoon, which show small increases (Figures 4.12 and 4.13). This pattern of growth becomes more distinct every 25 years into the future up to the year 2100 (Figures 4.12 and 4.13). CNRM-CM5 shows a similar pattern, but the increase in Scots pine growth northwest of Saskatoon is shown in 2025 and slowly transitions to no change in growth in 2100, and the predicted decreases in Scots pine growth are not as drastic as ACCESS1-0. In general, the probability that Scots pine future growth will be different from past growth is lower. Many of the p-values seen in Table 4.19 for all the models and RCP's are above the 0.05 significance level or just under. The models ACCESS1-0 and CNRM-CM5 tend to have lower p-values than CanESM2 and INMCM4, indicating that the probability of changes in future Scots pine growth are higher under these models.

Models CanESM2 and INMCM4 illustrate a similar pattern of predicted increases in Scots pine growth on the west side of the study area extending from west of Saskatoon through Kindersley to Swift Current and increases northeast of Saskatoon and around Regina for both RCP 4.5 and 8.5 (Figures 4.12 and 4.13). The CanESM2 model shows more extreme increases and decreases in Scots pine growth than the INM model.

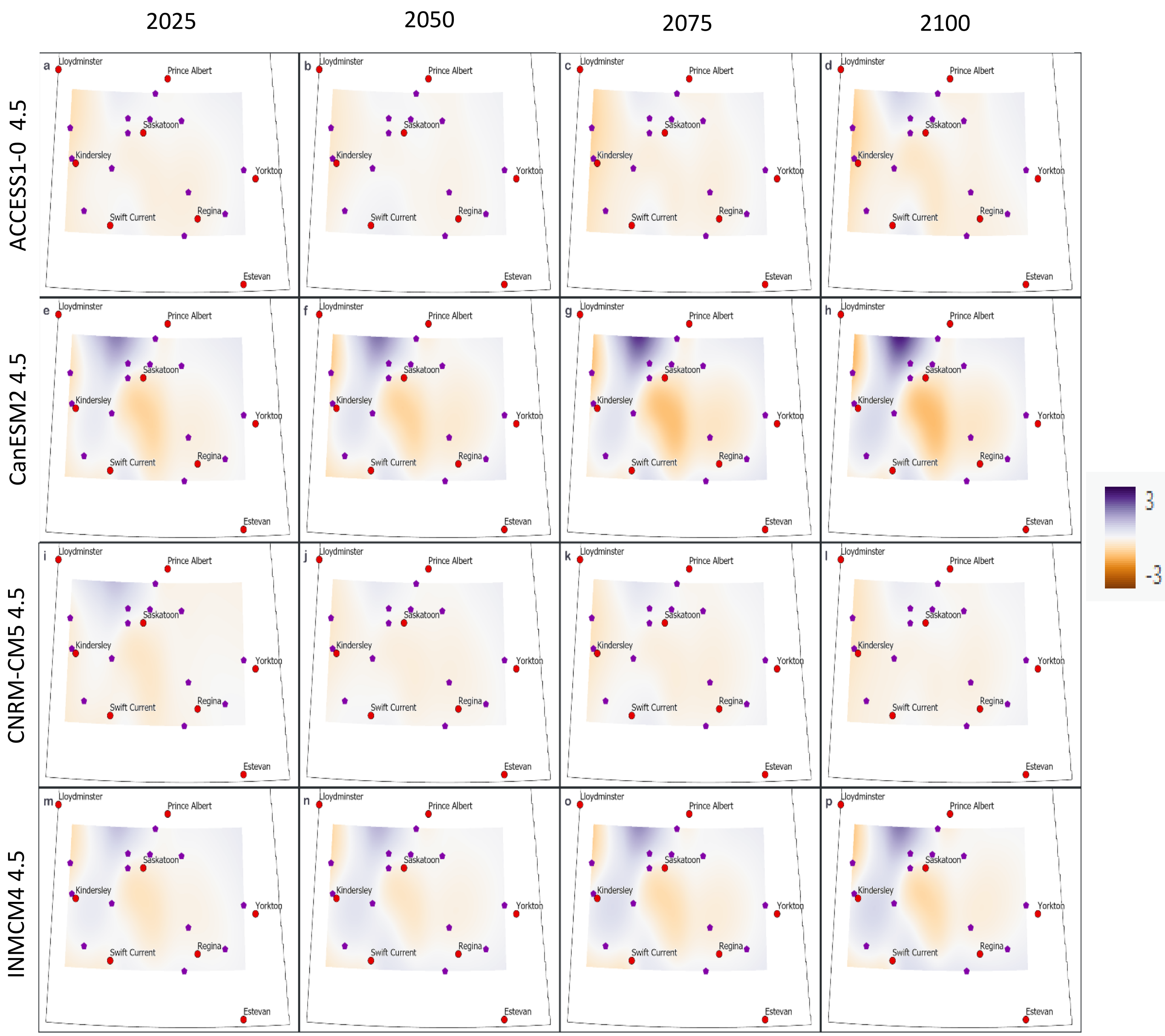

Figure 4.12 Mapped difference between past growth and predicted future growth of Scots pine until 2100 for four different climate models at the RCP 4.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

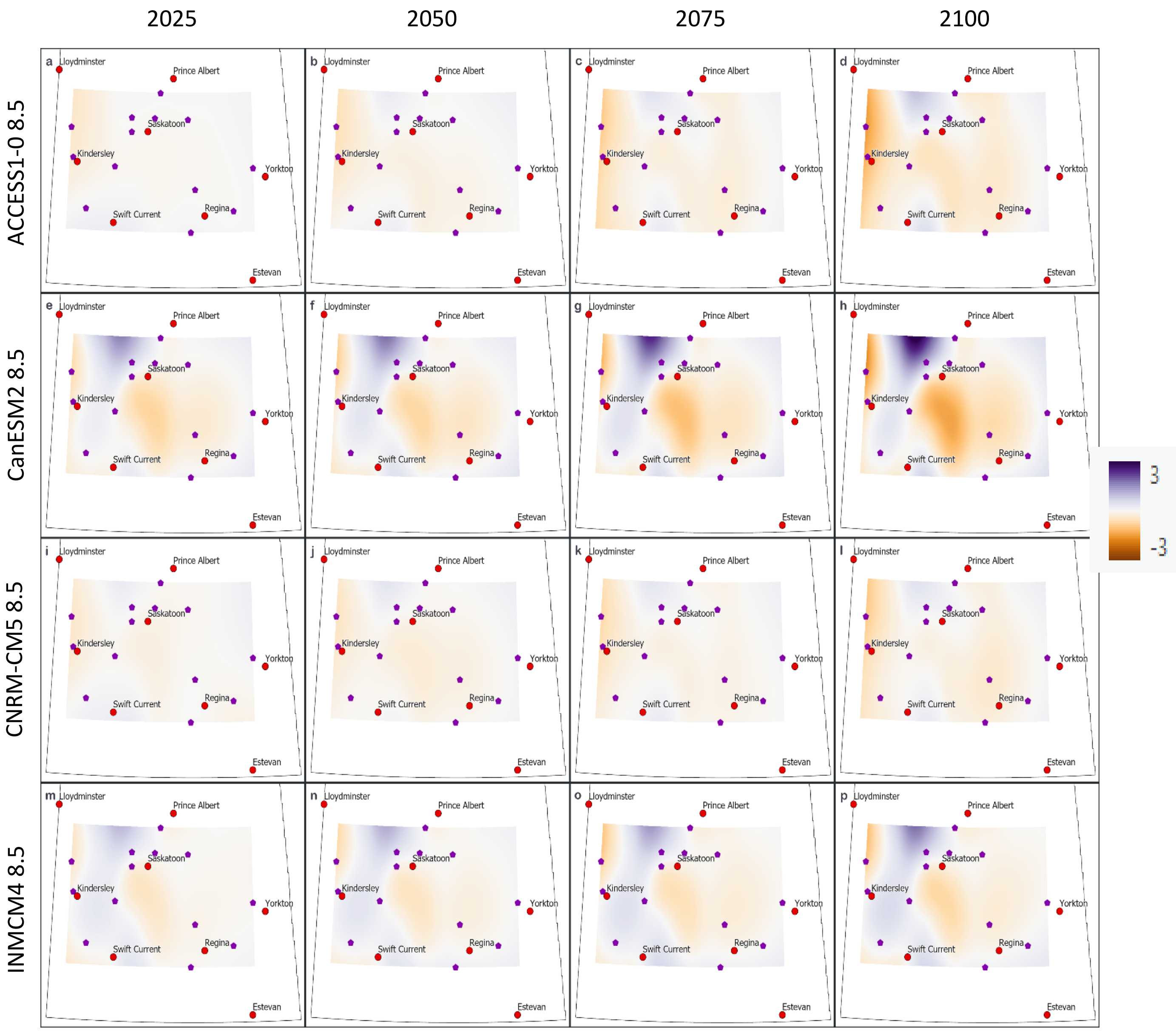

Figure 4.13 Mapped difference between past growth and predicted Scots pine future growth until 2100 for four different climate models at the RCP 8.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

Table 4.19 Probability that there is a difference between past and future Scots pine growth for the specific model, RCP, and 25-year time increment into the future. The lower the p-values, the higher the probability that there is a difference between past and future growth.

Global Climate Models for RCP 4.5 and 8.5	Scots pine p-values			
	Year			
	2025	2050	2075	2100
ACCESS1-0 4.5	0.0220621	0.0236313	0.0245864	0.0340664
CanESM2 4.5	0.4143001	0.4789215	0.6788642	0.9386300
CNRM-CM5 4.5	0.1005329	0.0225778	0.0465844	0.0418498
INMCM5 4.5	0.5229426	0.9255284	0.9563647	0.8194199
ACCESS1-0 8.5	0.1609612	0.0376760	0.0245388	0.0401299
CanESM2 8.5	0.4119315	0.6060601	0.6613036	0.4491422
CNRM-CM5 8.5	0.0646124	0.0278111	0.0530666	0.0350245
INMCM5 8.5	0.3700244	0.9301693	0.5696492	0.7615603

The overall pattern of predicted Scots pine growth is difficult to determine the reasoning behind changes based on the relative weights map (Figure 4.11). Predicted increases in Scots pine growth in the northwest corner of the study area (west of Saskatoon) are caused by Scots pine's positive relationship to June precipitation, which is predicted to increase in the future (Figure 4.6).The reason Scots pine growth is predicted to decrease in a large central area of Saskatchewan (south of Saskatoon and north, east, and west of Regina) is due to autumn and summer precipitation, and summer temperature. Autumn precipitation is predicted to increase according to future climate maps (Figures 2.3 and 2.5) and has a positive relationship with Scots pine meaning that growth should increase in the areas highly influenced by autumn precipitation (Figure 4.14g). Yet the teardrop shaped area south of Saskatoon, which shows a high influence of autumn precipitation in the relative weights map, predicts decreases in Scots pine growth. This is because the teardrop shaped area is based off of a site called 11ILS00, which is highly positively correlated to previous September precipitation (accounts for close to 30 % of R-squared, Table17), and September precipitation is predicted to slightly decrease in the future (Figure 4.15), resulting in the decrease in Scots pine radial growth in this area.

Summer precipitation, particularly previous June precipitation, close to Regina (site 18ZLS00) is negatively correlated to Scots pine, which explains the decrease in Scots pine growth in this area since June precipitation is predicted to increase (Figure 4.6). The area east of Regina (east corner of raster) is positively influenced by summer precipitation, particularly June precipitation, which explains why Scots pine is predicted to increase in this area. Summer temperature also plays a role in reducing Scots pine growth in the west side of the raster (especially for the models ACCESS1-0 and CNRM-CM5) and the east side close to Yorkton (Figure 4.14). Scots pine has a negative relationship to summer temperature, and summer temperature is predicted to increase, resulting in a decline in Scots pine growth. The increases in Scots pine growth around Swift Current area (shown mainly in ACCESS1-0 and CNRM-CM5) and the west side of the raster (shown mainly in CanESM2 and INMCM4) is attributed to Scots pine's positive relationship to spring precipitation, since spring precipitation is predicted to increase in the future (Figures 2.3 and 2.5). Figure 4.15 shows that not all autumn months are predicted to follow the general trend of increases or decreases. Autumn precipitation is expected to slightly increase in the future, but September precipitation is expected to see some minor decreases, whereas October and November precipitation are forecasted to increase (only previous October and November precipitation are included in the predicted Scots pine future growth).

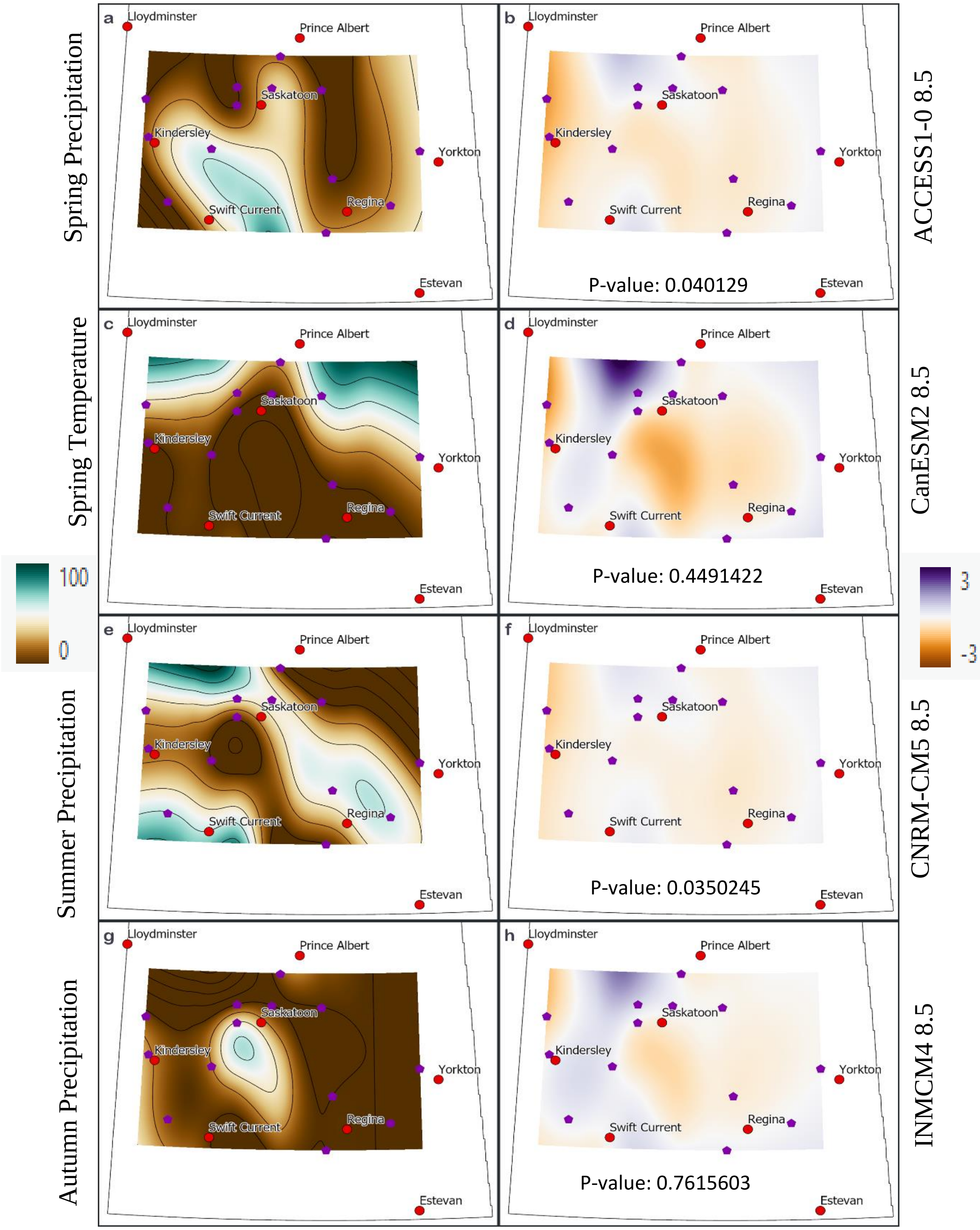

Figure 4.14 Spring precipitation and temperature and summer and autumn precipitation relative weights maps that identify areas where these precipitation and temperature variables have the highest influence in the southern half of Saskatchewan (maps a, c, e, g), compared to maps that predict changes in Scots pine growth for four climate models under the RCP 8.5 in the year 2100 (maps b, d, f, h).

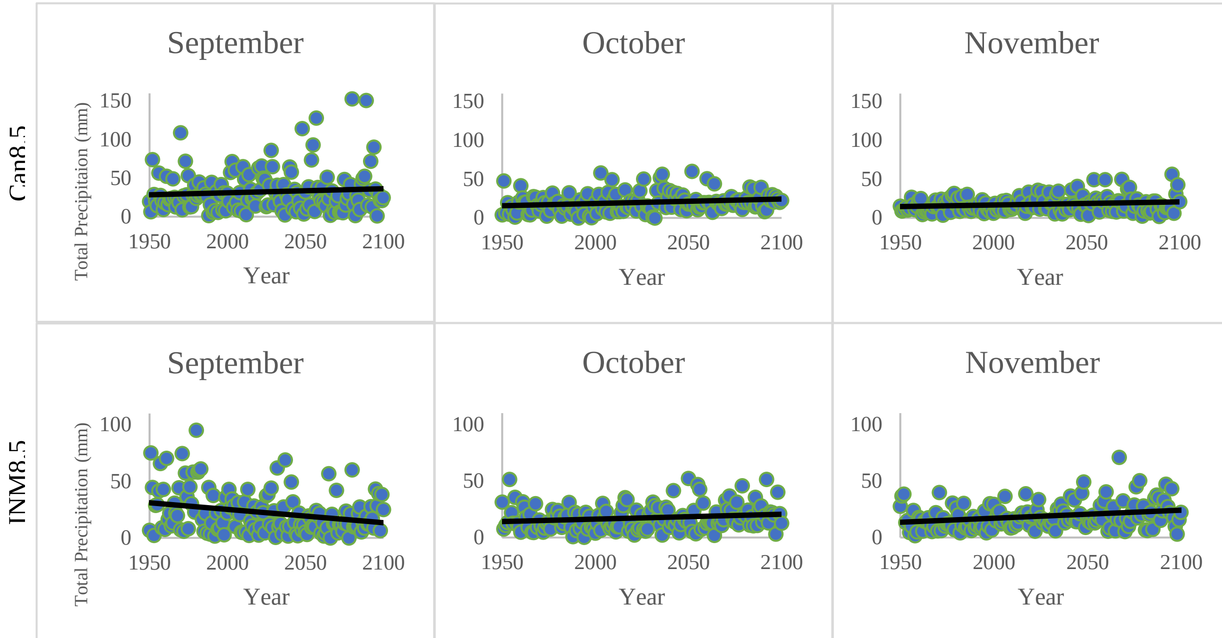

Figure 4.15 Trends in total precipitation (mm) for the season of autumn from 1950 to 2100 under the RCP 8.5 for the climate models CanESM2 and INMCM4 within a 10 km grid square located in south-central Saskatchewan (52.125˚, -107.21˚).

4.5 White Spruce

4.5.1 Relative weights

White spruce growth is mainly influenced by summer temperature and precipitation. The total sums of white spruce relative weights are close in value to each other, suggesting that the relative importance of climate variables is site specific (Tables 4.21 and 4.22). Current-June temperature and current-June precipitation are ranked as the first and second most influential climate variables for white spruce growth, followed by previous-August precipitation, current-July temperature, previous-June precipitation, and previous-February temperature.

The Swift Current area is positively influenced by spring precipitation and the northeast corner of the study area (north of Yorkton and east of Prince Albert) is negatively influenced by spring precipitation (site 12AIL200 in Table 4.22) and summer temperature (Figure 4.16 and Table 4.23).

The influence of spring precipitation on white spruce growth is dependent upon the site, since several sites show negative responses to spring precipitation (Table 4.22). Winter temperatures positively affect white spruce growth for sites southeast of Saskatoon and between Swift Current and Kindersley (12AAL200, 12ACL200, and 12OL200). Although three other sites show winter temperature has a negative influence on white spruce growth, their influence is not strong enough to show up on the relative weights map (Figure 4.16, Table 4.23). Summer precipitation positively effects white spruce growth in a large area expanding from Prince Albert southwest to Saskatoon and Swift Current, and east through Yorkton to Estevan. Autumn precipitation has a positive effect on white spruce growth south of Yorkton.

Table 4.20 White spruce relative weights of precipitation climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. White spruce sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

White Spruce	Previous Precipitation												Current Precipitation					
Site Name	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mar	Apr	May	Jun	Jul	Aug
12AEL200			36.0		19.5							25.1						
18VL200	11.2	16.4									15.3			26.4	22.3	8.4		
18KL200		10.8								30.1							33.5	
12ML200								35.5										
18SL200			19.1															
17HL200				15.7				31.4							34.1			
12AAL200	7.8				13.2													45.3
12ACL200																		
11ANL200		12.1										13.5			19.8	20.0		
12QL200																		
17DL200						21.0	6.8							32.8				
11ADL200	19.2								10.0							29.8		
12AHL200									44.6	17.1								
12NL200	12.2		9.1		16.2													
12ANL200							23.8							22.7				
15BL200					21.3	55.1												
12AIL200													29.7	12.7				8.3
17CL200				24.1														
12OL200																46.1		
12GL200								36.8										22.5
11JL200								17.8	35.6							15.1		
11GL200	30.6	11.4	20.9			37.2												
11DL200								11.0		26.0					18.6	44.4		
Total	80.9	50.7	85.0	39.8	70.2	113.2	30.5	132.4	90.1	73.2	15.3	38.6	29.7	94.5	94.8	163.8	33.5	76.1
Average	16.2	12.7	21.2	19.9	17.6	37.7	15.3	26.5	30.0	24.4	15.3	19.3	29.7	23.6	23.7	27.3	33.5	25.4

Table 4.21 White spruce relative weights of temperature climate variables. Relative weights are represented as percentages and identify how much (%) each climate variable contributes to each site's R-squared value and as a result ranks the relative importance of the climate variables. White spruce sites are organized from the most southern sites to the most northern sites. The ranking of how influential each climate variable is, is based on the total (sum) of relative weights. The climate variable with the largest total sum is considered the most influential.

White Spruce Site Name	**Previous Temperature**												**Current Temperature**					
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
12AEL200															19.5			
18VL200																		
18KL200																		
12ML200									6.9	12.4	20.0					25.3		
18SL200													12.9				68.0	
17HL200																18.8		
12AAL200		33.7																
12ACL200		15.1									22.3				25.5	37.1		
11ANL200					20.4				14.2									
12QL200								12.3					10.9	29.0	47.7			
17DL200														39.5				
11ADL200		8.4												21.3		11.4		
12AHL200				28.5						9.8								
12NL200								16.1							46.5			
12ANL200											17.7	35.9						
15BL200		23.6																
12AIL200									22.2		27.1							
17CL200						30.6							24.2				21.1	
12OL200	12.8	24.9																16.1
12GL200													11.4		29.4			
11JL200																31.5		
11GL200																		
11DL200																		
Total	12.8	105.7	0.0	28.5	20.4	30.6	0.0	28.4	43.3	22.1	87.0	35.9	59.4	89.9	168.5	124.1	89.1	16.1
Average	12.8	21.1	0.0	28.5	20.4	30.6	0.0	14.2	14.4	11.1	21.8	35.9	14.9	30.0	33.7	24.8	44.5	16.1

Table 4.22 The precipitation climate variables and their model coefficients that are used in the future growth model for each white spruce site across the southern half of Saskatchewan. Negative numbers show a negative correlation to climate variables and positive numbers indicate a positive correlation to climate variables. These climate variables combine previous and current year precipitation. Current year climate variables range from April-September and previous year range from January-December.

White spruce	Spring Precip			Summer Precip			Autumn Precip			Winter Precip		
Site Name	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
12AHL200							-0.003	0.003				
15BL200			0.004	0.004								
17CL200		0.005										
17DL200		0.005		-0.002	0.002							
12QL200				0.002								
18KL200					0.002		0.002	0.004				-0.005
11DL200			0.002	0.002		0.001		0.003				
12ML200						0.003						
11ANL200			0.003	0.002						0.006		-0.007
11GL200	0.007			0.004							0.008	-0.008
12NL200	-0.004		0.002								0.004	
12AAL200			-0.003			0.004					0.006	
18VL200		0.008	0.004	0.004					0.010			-0.013
11JL200				0.002		0.003	0.006					
11ADL200				0.003						-0.006	0.007	
12OL200				0.003								
12AIL200	-0.004	-0.002				0.001						
12AEL200	-0.008		-0.002							0.008		
17HL200		-0.002	0.002			0.002						
18SL200						0.002						
12GL200						0.002						
12ACL200												
12ANL200		-0.007			-0.005					0.009		

Table 4.23 The temperature climate variables and their model coefficients that are used in the future growth model for each white spruce site across the southern half of Saskatchewan. Negative numbers show a negative correlation to climate variables and positive numbers indicate a positive correlation to climate variables. These climate variables combine previous and current year temperature. Current year climate variables range from April-September and previous year range from January-December.

White spruce	Spring Temp			Summer Temp			Autumn Temp			Winter Temp		
Site Name	**Mar**	**Apr**	**May**	**Jun T**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
12AHL200		-0.015						0.019				
15BL200												-0.031
17CL200		-0.032		-0.058		-0.038						
17DL200			-0.051									
12QL200		0.032	-0.047									-0.025
18KL200												
11DL200												
12ML200					-0.039		-0.018	-0.021	0.022			
11ANL200			-0.038									
11GL200												
12NL200				-0.053		-0.022						
12AAL200												0.027
18VL200												
11JL200					-0.087							
11ADL200			-0.048		-0.053				-0.025			
12OL200							-0.018				-0.010	0.018
12AIL200							0.026		-0.021			
12AEL200				-0.045								
17HL200					-0.020							
18SL200		0.018				-0.021						
12GL200		-0.001		-0.047								
12ACL200				-0.029	-0.029				0.016			0.010
12ANL200									0.035	-0.040		

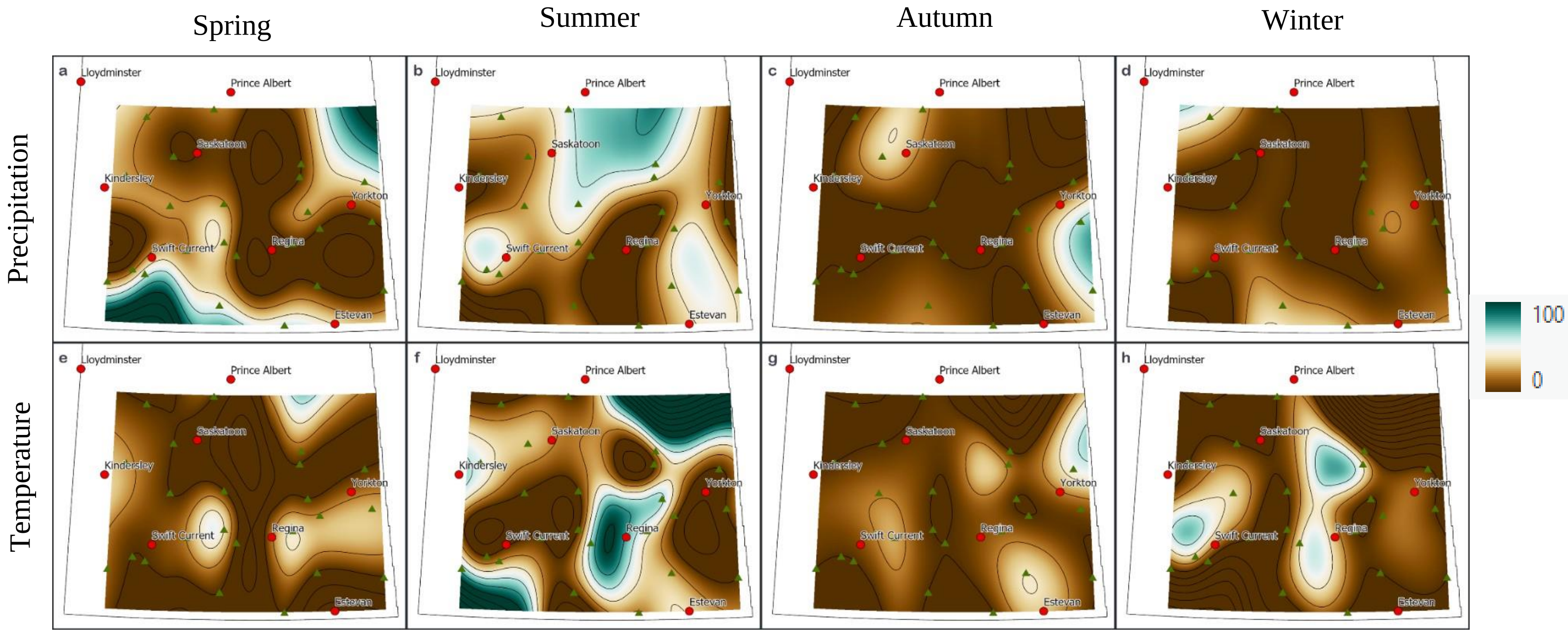

Figure 4.16 Mapped relative weights of precipitation and temperature variables used in white spruce future growth models. The blue areas show sites that are influenced by a climate variable and the brown areas are not influenced by the climate variable. The green triangles represent white spruce sites. The contour lines show the increasing or decreasing of value in increments of 20%. Current and previous climate variables are grouped together. Spring=MAM; Summer=JJA; Autumn=SON; Winter=DJF. Relative weights approximate in percent (scale of 0-100%), how much each climate variable contributes to the R-squared (total variance of tree-growth explained by climate).

4.5.2 Predicted Change in Future Growth

Predicted future growth maps (Figures 4.17 and 4.18) show that white spruce growth is predicted to decrease across most of the southern half of Saskatchewan for both RCP 4.5 and 8.5.These decreases become more pronounced every 25 years in the future. However, areas around Swift Current, Saskatoon, and Estevan show slight increases or a lack of changes in white spruce growth across all models, and a trend of increasing growth in these areas every 25 years into the future. The CNRM-CM5 model shows the smallest degree of changes in white spruce growth and CanESM2 shows the largest degree of changes. The northeast corner of the study area (southeast of Prince Albert and north of Yorkton) predicts large decreases in white spruce growth for CanESM2 and INMCM4 models, but a lack of data/sites in this region makes the decrease suspect. This northeast corner of the study map is likely interpolated based on sites nearby, and as a result may not be representative of the area since there are no sites that are close by. The probability that white spruce growth will change in the future is very high. All the climate models and RCPs show a statistical difference between past and future growth (very low p-values in Table 4.24).

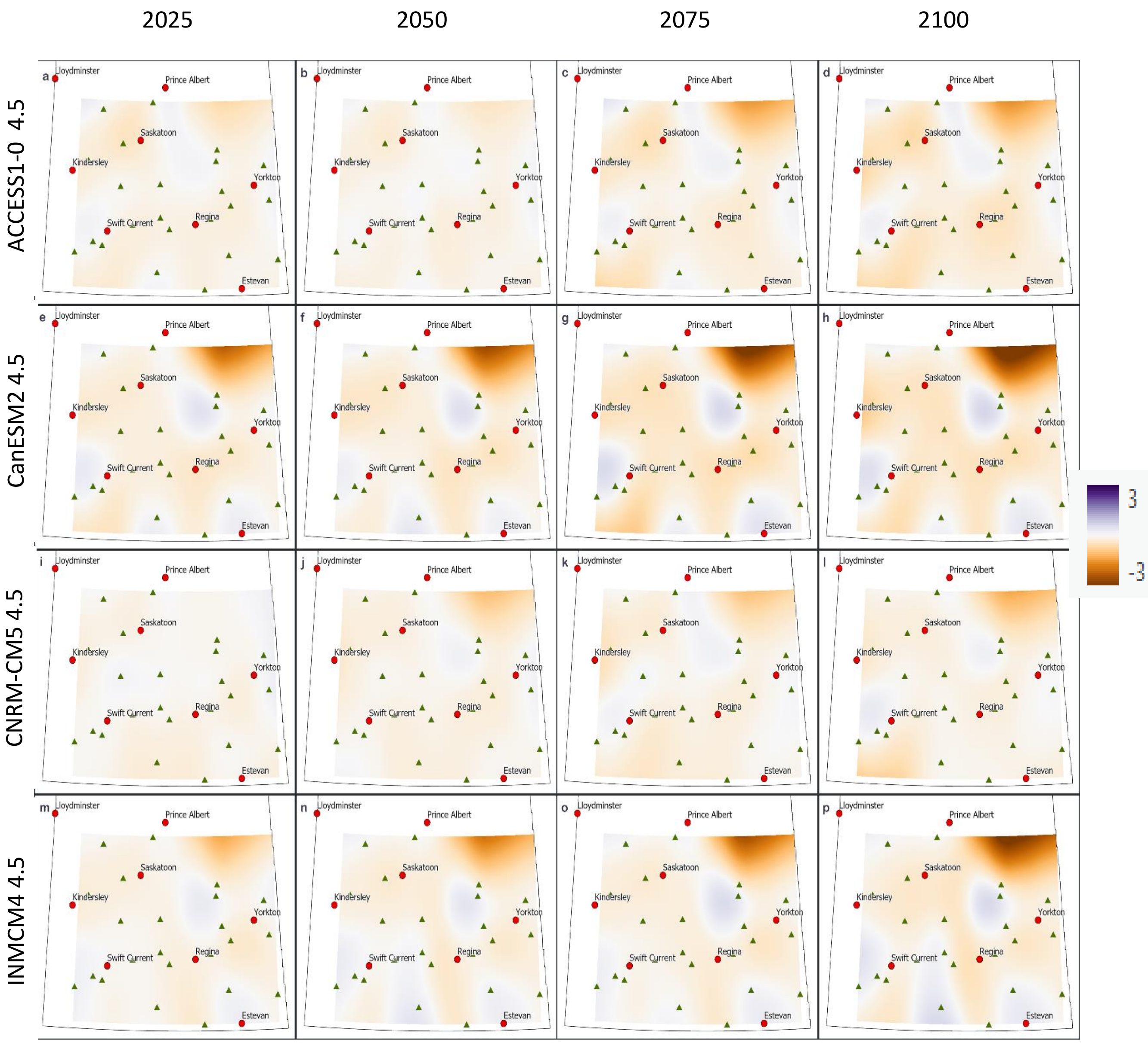

Figure 4.17 Mapped difference between white spruce past growth and predicted future growth until 2100 for four different climate models at the RCP 4.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

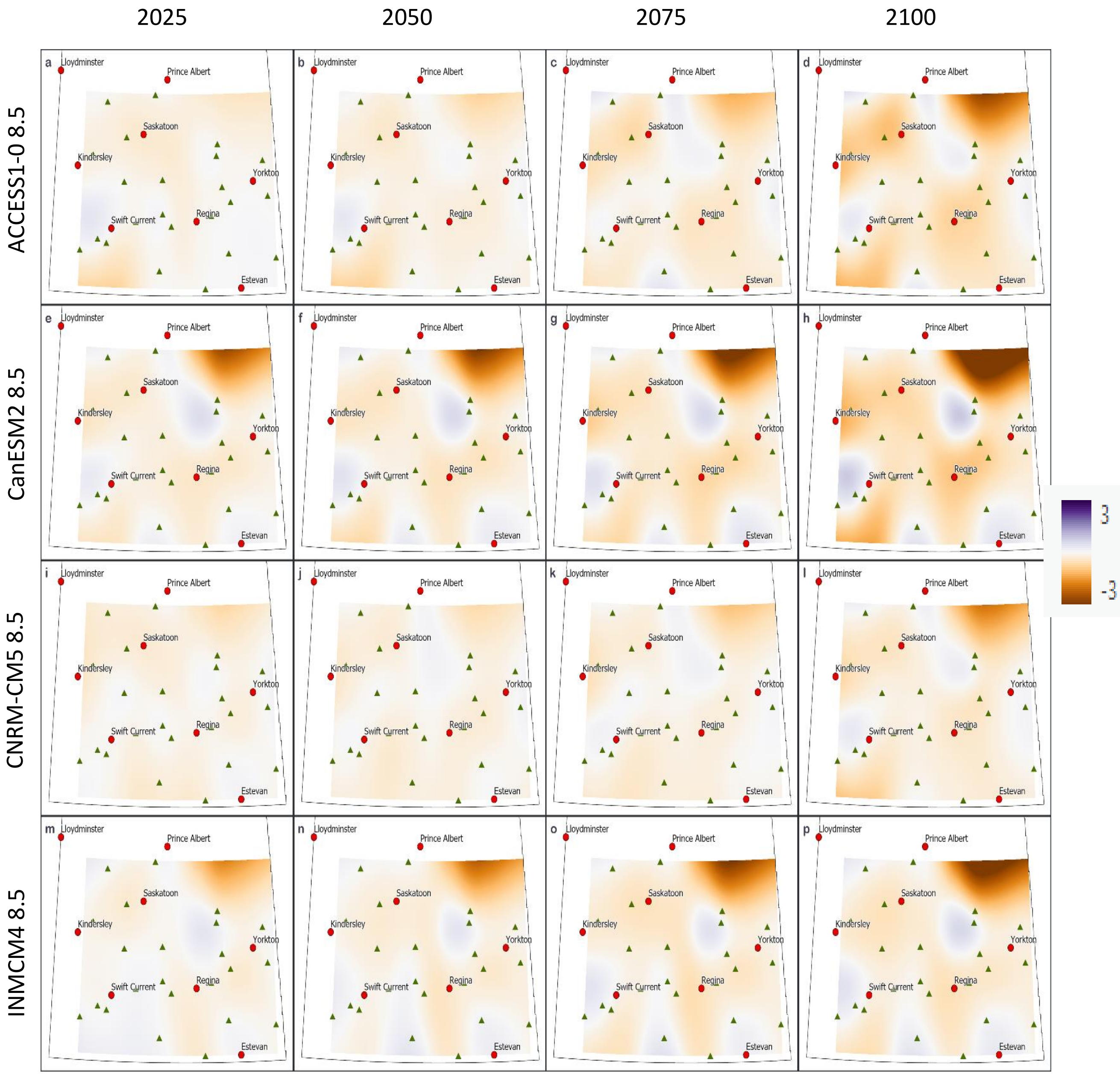

Figure 4.18 Mapped difference between white spruce past growth and predicted future growth until 2100 for four different climate models at the RCP 8.5. Split into 25-year increments so that changes throughout time can be seen. The scale (-3 to 3) represents an index of the difference from mean change in growth.

Table 4.24 Probability that there is a difference between past and future white spruce growth for the specific climate model, RCP, and 25-year time increment into the future. The lower the p-values, the higher the probability that there is a difference between past and future growth.

Global Climate Models for RCP 4.5 and 8.5	**White spruce p-values**			
	Year			
	2025	**2050**	**2075**	**2100**
ACCESS1-0 4.5	0.0000217	0.0000290	0.0000260	0.0000098
CanESM2 4.5	0.0001045	0.0002148	0.0001174	0.0002388
CNRM-CM5 4.5	0.0002614	0.0000022	0.0000421	0.0000051
INMCM5 4.5	0.0003421	0.0131099	0.0007000	0.0166238
ACCESS1-0 8.5	0.0040515	0.0000045	0.0000648	0.0000166
CanESM2 8.5	0.0001540	0.0005643	0.0001951	0.0001247
CNRM-CM5 8.5	0.0002449	0.0000040	0.0000178	0.0000440
INMCM5 8.5	0.0044220	0.0034487	0.0005878	0.0005599

Predicted decreases in white spruce radial growth are mainly caused by rising June temperatures under climate change conditions. Areas where white spruce growth is affected by summer temperature (JJA) in the relative weights map (Figure 4.19b), closely matches the pattern of decreasing white spruce growth across all models (Figure 4.19c, 4.19f, 4.19i, 4.19l). This match further indicates that expected increases in summer temperature, particularly June temperature, has a large negative effect on white spruce. Areas where there is a lack of change or a slight increase in white spruce radial growth are generally shown on the relative weights maps as areas that are not affected by summer temperature.

These areas of increases/lack of change in white spruce growth include a circular area between Saskatoon, Yorkton, and Regina, areas near Swift Current, and the Yorkton area. The area of increase between Saskatoon, Yorkton, and Regina is not correlated to summer temperature, and is highly positively affected by spring precipitation, current-June precipitation, and winter temperature (Tables 4.22 and 4.23). June precipitation and February temperatures are expected to increase in the future, thus positively influencing white spruce trees at this site. Near Swift Current, white spruce are expected to see slight increases to no change in white spruce growth because the area is not affected by summer temperature (Figure 4.19e), and is positively affected by predicted increases in spring precipitation (Figure 4.19a). The area of increase/lack of change in white spruce growth southwest of Swift Current, is likely attributed to the fact the area is not affected by summer temperature and is positively influenced by spring precipitation and summer precipitation (current June precipitation), which are predicted to increase in the future. Increases or lack of growth changes in white spruce growth in the Yorkton area seen in models ACCESS1-0 and CNRM-CM5 (Figure 4.19c, 4.19i), are likely because there is no relation to summer temperature in the area (Figure 4.19e), and the positive response of white spruce to predicted increases in autumn precipitation (Figure 4.19g). Lastly, the Estevan area that shows increases in white spruce growth in the models CanESM2 and INMCM4, likely because the area is based on the interpolation of the site 12ML200, which is positively influenced by previous-November temperature (Table 4.23), since winter temperatures expected to rise in the future.

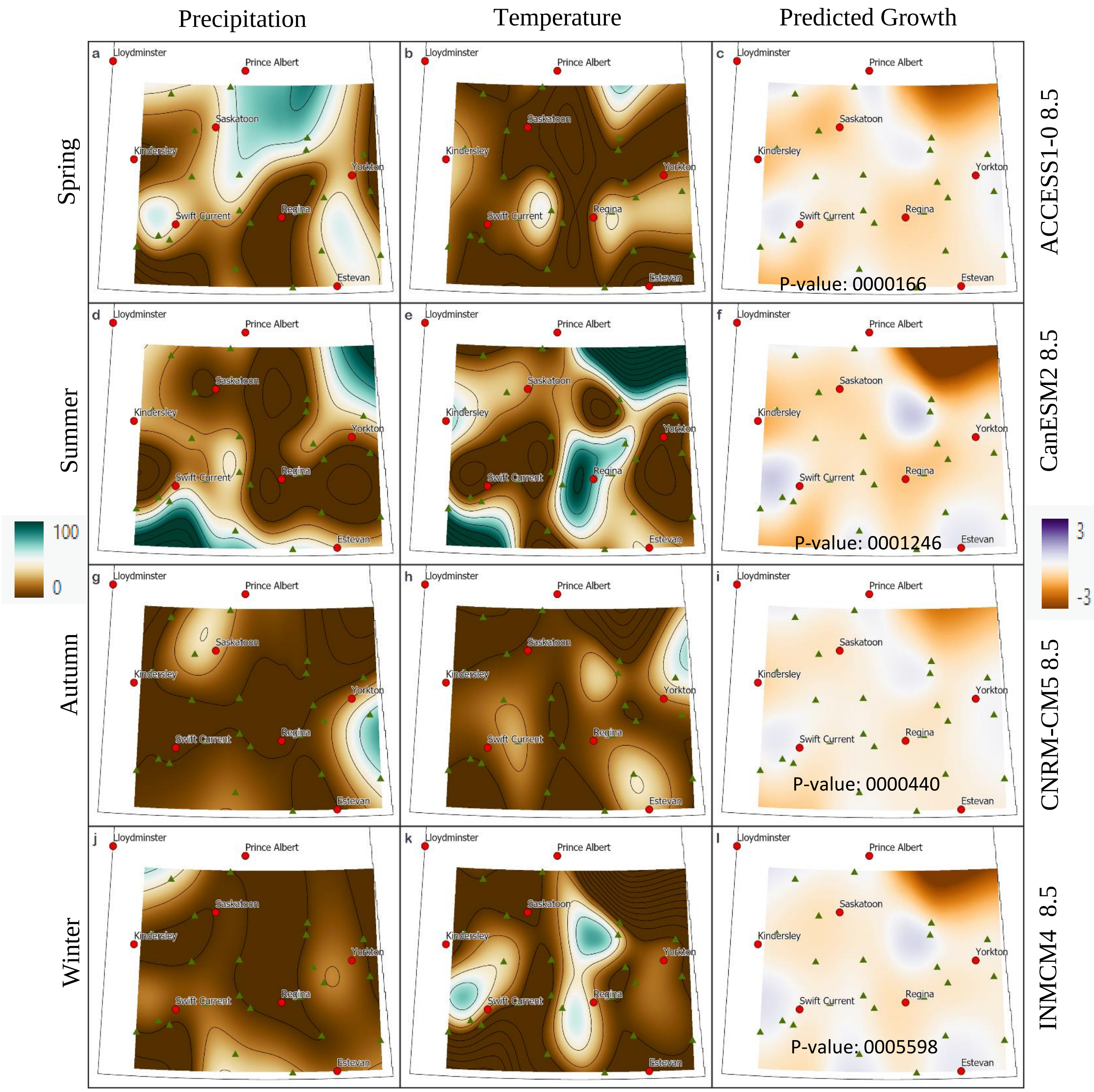

Figure 4.19 Relative weights maps of spring, summer, autumn, and winter precipitation and temperature, identify areas where climate variables have the highest influence on white spruce growth in the southern half of Saskatchewan (maps a, b, d, e, g, h, j, k), compared to maps that predict changes in white spruce growth for four climate models under the RCP 8.5 in the year 2100 (maps c, f, i, l).

5 DISCUSSION

5.1 General Chronology Characteristics

The high mean series intercorrelation, mean sensitivity, and R-squared values of all four shelterbelt species are consistent with the results from a study by Davis et al. (2013), which found that all these species are useful for dendrochronology purposes. Both my study and the study by Davis et al. (2013) found that white spruce had the highest mean series intercorrelation value followed by green ash, hybrid poplar, and Scots pine. This result indicates that white spruce has the strongest relationship between samples taken at the same site.

Green ash had the lowest average mean sensitivity value of all the shelterbelt species, likely because green ash is native to areas south of Saskatchewan and has moderate to high drought tolerance, making the trees less sensitive to climate in southern Saskatchewan (Agriculture and Agri-Food Canada, 2006). Typically, trees closer to the edge of their range are more sensitive to climate and are considered the best trees for studying dendroclimatology since they are more likely to record climate effects (Speer, 2012). Despite the lower AMS value, green ash is still considered highly sensitive to climate based on a scale developed by Grissino-Mayer (2001).

A study by Davis et al. (2013) found that hybrid poplar had a high mean series correlation value, but low mean sensitivity and low climate explanatory power. Similar to this study we found that hybrid poplar had a high mean series correlation value and low climate explanatory power, but unlike this study, hybrid poplar had a high mean sensitivity. Generally, when there is a high mean sensitivity you would expect to see a high climate explanatory power. This lack of high explanatory power could be in part due to the maintenance of shelterbelts, such as fertilizing and watering during the growing season (Rempel, 2014). Established shelterbelts are often cared for inconsistently, for example the trees may be watered in a dry year, or the trees may be fertilized once in a while if the producer decides to use up the remaining fertilizer when finished seeding. These inconsistencies could cause large changes in year-to-year variability in ring-widths and is likely exacerbated by the fact that hybrid poplar is one of the fastest growing shelterbelts and tends to put on large tree-rings in good growth years.

Scots pine was ranked as the least useful out of nine shelterbelt species for dendrochronology purposes in a study by Davis et al. (2013). The reason Scots pine was ranked the least useful in

Davis et al.'s study (2013) was because the inter-series correlation value and the relative abundance of trees in Saskatchewan was low. In my study, although I agree with Davis et al., (2013) that my Scots pine had the lowest mean series intercorrelation value, it was still well above the minimum significant value of 0.4226; however, the low abundance of trees made it difficult to find sites. I was able to take my study further, and the high mean sensitivity and R-squared values indicates that climate explains much of the variance in Scots pine ring-width when they are found.

White spruce had the highest average mean sensitivity, indicating that white spruce is highly sensitive to climate in southern Saskatchewan. This high sensitivity is likely attributed to the fact that white spruce is adapted to the boreal forest and boreal transition zone regions in Saskatchewan and typically struggles in southern Saskatchewan (Agriculture and Agri-Food Canada, 2006). It was difficult to find white spruce shelterbelts in southern Saskatchewan, since white spruce tends to do poorly under the low precipitation, high temperatures, and high evapotranspiration conditions typical of southern Saskatchewan (Zwiazek, 1991; Barber et al., 2000). In order to keep white spruce alive under these low soil moisture conditions, they were likely watered. However, the level of maintenance would vary for each site, and this likely had an effect on the mean sensitivity and R-squared values. A study by Maillet et al., in 2017 studied green ash and white spruce in shelterbelts in southeastern Saskatchewan. The study found that autocorrelation values decreased, and mean sensitivity increased when white spruce sites were located further to the south. Lower autocorrelation values and high mean sensitivity has been identified throughout the literature to be a characteristic response to drought stress, indicating that white spruce growing in more southern locations in southeastern Saskatchewan were highly stressed (Rigling et al., 2002). This pattern was not found in our study and it could be because the study by Maillet et al. (2017) only looked at southeastern Saskatchewan, whereas my study explored both latitude and longitude. Also, the maintenance of white spruce shelterbelts that I did find could have affected this pattern.

Although white spruce had the highest MSI, and AMS values, indicating a strong relationship between trees at the site and climate, it's R-squared values were low showing that the variability in white spruce tree rings did not explain the variance in climate as well. This is likely because white spruce needs to be kept alive through maintenance, which makes it difficult to study climate change effects in white spruce in southern Saskatchewan. Green ash is more drought tolerant and hardy yet is still sensitive to climate and does not need as much maintenance to stay alive under Saskatchewan conditions. It is also an abundant tree throughout Saskatchewan and has high MSI and AMS values, indicating that it is an excellent tree to use for dendrochronological studies.

Hybrid poplar also appears to receive a fair amount of maintenance to stay alive and does not have as strong of a relationship to climate. Scots pine overall has a relatively strong relationship with climate and between trees at the same site (AMS, R-squared values, and MSI values), but is challenging to find across Saskatchewan, making it a difficult to study.Climate variables that influence growth

5.1.1 Green ash

Similar to previous studies by Davis et al. (2013) and Maillet et al. (2017), green ash growth is mainly influenced by precipitation in May and June and moisture in these months are considered the most important variables affecting green ash growth (current June precipitation is considered the most influential climate variable on green ash growth, followed by current May precipitation, and previous June precipitation). Current May temperature ranks as the fourth most important factor contributing to green ash growth (Table 4.6) and appears to have the largest impact on the western and northern areas of the study area. The western side of Saskatchewan is highly influenced by the rain shadow from the Rockies, and tends to be drier, with high spring and summer temperatures (Fuller, 2010). These high temperatures are conducive to high evapotranspiration rates leading to spring and early summer soil moisture deficits. This lack of soil moisture is likely the most limiting factor to green ash growth in this area, which explains why spring and summer temperatures have a large impact on green ash growth in the western side of the province.

The reason the northerly green ash sites are more affected by spring and summer temperature could be explained by a shift in the climate-growth relationship. , Current May temperature does not influence growth in the seven most southerly sites but does in the more northern sites, and previous June precipitation does not influence growth in the five most northerly sites but instead affects growth in the more southern sites, indicating a shift from the importance of spring precipitation to spring temperature as you go north (Tables 4.5 and 4.6). A study by Maillet et al.

(2017) also saw this pattern and suggested that green ash in more northerly sites depended less upon spring precipitation since there is more moisture at higher latitudes. The observed shift in the growth-climate relationship indicates that green ash are stressed at more northern sites (Prince Albert area) (Büntgen et al., 2006; Misi et al., 2019). Since green ash is drought tolerant and is adapted to southern Canada, it likely becomes stressed when pushed towards its northern boundary

5.1.2 Hybrid poplar

The most influential climate variables controlling the variability in hybrid poplar radial growth were previous August temperature, current May temperature, current June precipitation and temperature, and previous September precipitation (Appendix Table A.2). Other studies have found similar results that hybrid poplar growth is mainly driven by the previous growth season's late summer and early fall precipitation and temperature (Chhin, 2010; Davis et al., 2013). These studies hypothesized that the level of soil moisture in the late summer and early fall of the previous growth season determined the amount of carbohydrate reserves that were able to be stored to drive growth in the following season. Saskatchewan is semi-arid, meaning that the low precipitation and high temperatures typical of Saskatchewan (low soil moisture), likely limit the carbohydrate reserves that can be stored in the fall to drive hybrid poplar diameter growth in the following spring. Once the carbohydrate reserves are depleted in the spring of the following growth season, hybrid poplar must depend upon good soil moisture in the spring and early summer. The importance of spring and early summer conditions is not seen in the study by Chhin (2010), likely because the study was located in Michigan, which receives more moisture than Saskatchewan and has a longer growing season, enabling the trees more time to store carbohydrates in the late summer and fall. It was also not seen in the study by Davis et al. (2013), likely because of the limited number of sites that were located closely together.

5.1.3 Scots pine

Previous studies agree that spring and summer precipitation and summer temperature are the main factors driving Scots pine growth (Michelot et al., 2012; Misi et al., 2019). In semi-arid places such as Saskatchewan, spring and summer precipitation, particularly May and June precipitation (Current June precipitation ranked the most important climate variable influencing Scots pine growth, current May precipitation (3rd), previous June precipitation (4th) is considered the most limiting factor, and the amount of May and June precipitation received each year largely influences the variability in year-to-year ring-width (Misi et al., 2019). Other factors that control soil moisture in the summer, such as previous-August temperature (ranked second most important climate variable), also limit Scots pine radial growth and affect the amount of carbohydrate reserves Scots pine are able to store to drive growth in the following season. Although spring temperature is not considered to have as strong of a relationship to Scots pine growth (has a lower relative importance), it has a large effect on more northern sites as seen in Figure 4.11 and Table 4.20. It has been hypothesized that this positive relationship to spring temperature (Table 4.19) is because warmer spring temperatures melt snow cover and promote soil water infiltration, and kickstarts Scots pine photosynthesis at the beginning of the growing season (Misi et al., 2019). Studies have found that Scots pine's relationship to spring temperature is breaking down and becoming less important under warming conditions (Jacoby and D'Arrigo, 1995; D'Arrigo et al., 2008; Misi et al., 2019). This phenomenon is called divergence and is likely happening because higher temperatures disturb the dehardening of the trees, making them more vulnerable to early spring frost (D'Arrigo et al., 2008). A paper by D'Arrigo et al. (2008), reviewed the current literature published on divergence studied across numerous circumpolar northern latitude sites, and found that many of the studies concluded divergence was occurring in these areas. We could be seeing divergence in the Scots pine relative weights map (Figure 4.11), because only the more northern sites are highly influenced by spring temperature, which suggests that the spring temperature-relationship boundary is being pushed northward by warming conditions.

5.1.4 White spruce

It is well known that the southern limit of white spruce is the aspen parkland, because white spruce growth is mainly driven by moisture stress (Chhin and Wang, 2008). It is typical of conifer growth to respond mainly to summer precipitation and temperature (Barber et al., 2000; Chhin and Wang, 2002; Davis et al., 2013; Maillet et al., 2017; Misi et al., 2019), and my study was no exception. White spruce relative weights show that current-June temperature had the largest effect on white spruce growth followed by current-June precipitation, previous-August precipitation, current July temperature and previous-July precipitation (Tables 4.17 and 4.18). A study by Chhin and Wang (2008) that looked specifically at white spruce growth on the

Saskatchewan prairies, found the same results, that white spruce growth is highly influenced by the month of June. June temperature negatively affected growth and June precipitation positively affected white spruce growth, in both our study and the study by Chhin and Wang (2008), suggesting that soil moisture during this time is critical for white spruce growth. White spruce's negative relationship with June and July temperature indicate that higher summer temperatures are likely causing temperature-induced drought in white spruce. Additionally, these higher summer temperatures increase evapotranspiration, leading to soil moisture deficits, further stressing white spruce.Similar to Scots pine and hybrid poplar, the late-summer climate variables of the previous growing season affect how much carbohydrate reserves can be stored to use for white spruce growth in the following growth season. White spruce is positively correlated to previous July and August precipitation, indicating that with more precipitation, white spruce is able to store more carbohydrate reserves (Misi et al., 2019). The dry and hot Saskatchewan prairie environment is predicted to become even drier and hotter under climate change, suggesting that white spruce, which typically grows well under cool and moist conditions, will likely not fare well under future climate conditions.

5.1.5 Summary of common climate variables influencing growth

All four shelterbelt species in this study were largely influenced by spring/early summer conditions. Current June precipitation is listed as one of the top three most influential climate variables for all four shelterbelt species. May precipitation or temperature greatly influences green ash, hybrid poplar, and Scots pine but is not considered as important for white spruce growth in southern Saskatchewan. This does not mean May precipitation and temperature are not important for white spruce growth, it indicates that high summer temperatures that induce drought-stress have a greater influence on white spruce growth than May conditions. All tree species store carbohydrate reserves to kickstart growth the following spring. This is especially important for hybrid poplar growth. Hybrid poplar relies upon adequate soil moisture in late summer and early fall to store carbohydrate reserves, thus late summer and early fall conditions have a high influence on hybrid poplar growth. Other studies often do not include spring and early summer climate variables as highly influential climate variables on hybrid poplar growth like this study does (Chhin, 2010; Davis et al., 2013). This indicates that hybrid poplar in these other studies were growing in regions where they received adequate precipitation in early summer/late fall, whereas most areas in this study were drier and hybrid poplar needed to rely upon both good soil moisture in late summer and early fall and in the spring to drive growth.Similarly, Scots pine and white spruce indicate that they require more soil moisture to drive growth, but in the opposite way of hybrid poplar. Most previous studies found that Scots pine and white spruce rely largely upon spring and early summer soil moisture for good growth (Chhin and Wang, 2008; Michelot et al., 2012; Misi et al., 2019), but in more moisture limited regions, white spruce and Scots pine were also highly influenced by previous late summer and early fall climate variables (Davis et al., 2013; Maillet et al., 2017). This is likely because Scots pine and white spruce need to take advantage of previous late summer and early fall moisture to store carbohydrate reserves in order to survive dry conditions in May and June. Green ash is not as reliant upon the previous season's soil moisture to store reserves, because it is more drought tolerant and can take advantage of May and June precipitation to drive growth.

5.2 Limitations of model

The model used in this study is limited because it only uses climate to explain radial growth in shelterbelt trees. Other factors that influence tree growth include; maintenance provided by the landowner for the shelterbelt trees, insect damage, and soil type. Another disadvantage of this model is that it assumes that because a tree responded in a particular way to a certain climate variable that it will continue to respond it that way under future conditions. It is possible that a response to a climate variable may change and/or there may be a shift and another climate variable will become highly influential to radial growth. It is difficult to predict when or if this will happen.

As climate change progresses, extreme climate events are predicted to increase (Bush and Lemen, 2019). Climate models have improved immensely over recent years in their ability to simulate these extreme events, but still have issues simulating extreme precipitation events (Flato et al., 2013). Instead, climate models often have drizzle issues, meaning they predict smaller and more precipitation events than will likely occur. As a result, the climate models may not capture some of these extremes, which negatively affects the accuracy of the model used in my study. White spruce growing south of the aspen parkland region often rely upon human intervention to establish them and keep them alive. The varying types and degrees of maintenance these trees receive, provides a possible explanation to why certain white spruce sites respond differently to climate than their neighboring sites (Maillet et al., 2017). The more care and maintenance these trees receive, the more likely there will be a breakdown in the growth-climate relationship because human intervention begins driving growth. There is evidence of this breakdown in the white spruce model coefficient tables (Tables 4.22 and 4.23), because there is a mix of positive and negative coefficients, illustrating that neighboring sites have different responses (negative or positive) to the same climate variables. White spruce sites not responding to rising June temperatures likely receive enough water during June to avoid temperature induced drought and deficient soil moisture conditions. If these sites were not watered, it is expected that June temperature would limit their growth, similar to other sites, and white spruce radial growth would decrease across the Brown, Dark Brown, and Black soil zones of Saskatchewan. Green ash, hybrid poplar, and Scots pine are also often watered and receive maintenance, but white spruce likely receives the most care because it has little tolerance to drought.

A major problem that green ash is facing is an invasive beetle from Asia called the emerald ash borer (EAB). The EAB has not yet been found in Saskatchewan but was found in Winnipeg in the fall of 2017 (Anderson, 2019). Once EAB populations are established they can decimate green ash trees in an area, and if they spread to Saskatchewan, they pose a major threat to green ash shelterbelt stands (Government of Saskatchewan, 2017).

Soil texture, pH and fertility will affect shelterbelt growth and landowners will need to ensure that they are choosing the right shelterbelt for their soil type. Scots pine can withstand sandy soils but prefer loam, and green ash can be planted in more clayey soils (Agriculture and AgriFood Canada, 2006). Hybrid poplar and white spruce tend to grow best in loam soils.

Hybrid poplar was very difficult to collect and process. At many of the sites, the hybrid poplar trees were too young, but the trees had not yet begun to rot, and the sites where the trees were old enough, many of the trees had begun to rot and the rings were difficult to see. As a result, many tree cores that were collected in AGGP1 and AGGP2 could not be used and there were fewer hybrid poplar sites.

5.3 Predicted future growth

Predicted increases in green ash growth across most of southern Saskatchewan is mainly attributed to predicted increases in May and June precipitation under future climate models. This is because green ash growth is mainly driven by May and June soil moisture conditions. However, in the more westerly areas of Saskatchewan, where the rain shadow affect from the Rockies has more influence, and less precipitation and rising temperatures induce drought stress in green ash, resulting in decreases in green ash growth. Under both RCP 4.5 and 8.5, the models ACCESS1-0 and CNRM-CM5 show a high probability that future green ash growth will be significantly different than past growth. Green ash future growth is generally not significantly different from past growth for CanESM2 under RCP 4.5, but is significantly different under RCP 8.5. INMCM4 shows extremes in both increases and decreases in green ash growth, yet predicted future growth is not significantly different from past growth. This could be because the t-tests conducted in this study used past average radial-growth and future predicted radial growth for all sites across the study area. The dramatic increases and decreases in green ash growth may have counteracted with each other, resulting in similar average predicted future growth and past growth.

Models ACCESS1-0 and CNRM-CM5 suggest growing conditions in the northeast corner of the study area (north of Yorkton and east of Prince Albert) could be good for green ash growth, because of increasing precipitation. This could indicate that the boundary for green ash growth is moving northward as more arid conditions move north. This increase in green ash growth under future climates suggests that it is one of the more resilient shelterbelt trees to climate change and may be a good choice for many landowners in southern Saskatchewan.Hybrid poplar growth is expected to slightly decline under future climates. This decline in growth is small because rising summer temperatures that reduce hybrid poplar growth are counteracted by increases in autumn precipitation which increase hybrid poplar growth. Rising summer temperatures have a larger negative effect on hybrid poplar and thus result in slight decreases in hybrid poplar growth. Changes in predicted future growth are significantly different from past growth for the climate models ACCESS1-0, CanESM2, and CNRM-CM5 under RCPs 4.5 and 8.5, but is not significantly different from INMCM4. This is likely because INMCM4 predicts less changes in precipitation and temperature than the other models. Since decreases in hybrid poplar growth are small, it will likely fare well in southern Saskatchewan if it is watered and maintained throughout the growing season. Hybrid poplar is expected to remain one of the most dominant trees to grow well and grow fast in the future, because of the minor predicted changes in hybrid poplar in this study and because of its popularity as a fast-growing shelterbelt.

Once again, the models CanESM2 and INMCM4 have higher p-values, indicating that the probability of changes in future Scots pine growth is small. However, their maps show more dramatic changes than the ACCESS1-0 and CNRM-CM5 models do. These higher p-values for CanESM2 and INMCM4 could be because the predicted dramatic increases and decreases in Scots pine growth counteract one another resulting in a similar predicted future average radial growth to past average growth. Scots pine growth is predicted to increase in the northwest (northwest of Saskatoon) under the climate models ACCESS1-0 and CNRM-CM5 and increase in both the northwest and western areas of the study area under CanESM2 and INMCM4. The increases in Scots pine growth in the west is mainly attributed to the predicted future increases in June precipitation, since Scots pine is largely influenced by soil moisture in June. Scots pine sites in the northwest corner of the study are highly positively influenced by spring temperature. Since spring temperatures are expected to rise in the future, and in response Scots pine growth in the northwest is predicted to increase.

This relationship between Scots pine and spring temperature is only seen in these more northern sites because typically these areas have colder temperatures, and warmer springs help to kickstart Scots pine growth and melt snow to promote increases in soil moisture. In more southern sites, the relationship between spring temperature and Scots pine growth has low relative importance, which likely means that spring temperatures are adequate and higher temperatures are not needed to kickstart growth. Past studies have found that the relationship between spring temperature and Scots pine is breaking down because of climate change induced rising spring temperatures, and that warmer spring temperatures may have a negative influence on Scots pine growth (Jacoby and D’Arrigo, 1995; D’Arrigo et al., 2008; Misi et al., 2019). This negative influence from warmer spring temperatures is likely because rising temperatures can disrupt the dehardening oftrees in the spring, making them more vulnerable to frost damage. Since past Scots pine growth is positively correlated to spring temperatures, the model in my study assumes that continuous increases in temperature will increase Scots pine growth. However, based on the studies by D’Arrigo (1995), D’Arrigo et al., (2008), and Misi et al. (2009), Scots pine might reach a threshold where spring temperatures become too warm and growth will not be as greatly influenced by spring temperature (spring temperatures are adequate) or will be negatively influenced by rising spring temperatures. Since Scots pine is somewhat drought tolerant and responds positively to increases in spring temperature in more northern sites, landowners in north-central Saskatchewan will likely continue to have success with Scots pine. Landowners located in more southern areas of Saskatchewan will need to water and maintain Scots pine to keep them alive under climate change conditions.

White spruce is adapted to the cool and moist boreal forest ecoregions of Canada, and presently does not grow well in southern Saskatchewan. Currently, landowners can grow white spruce relatively successfully in the aspen parkland ecoregion, but future maps show that white spruce growth is predicted to significantly decrease across southern Saskatchewan, including the aspen parkland ecoregion. This suggests that the boundary where white spruce is able to grow will be pushed northward by climate change (Hogg and Schwarz, 1997; Chhin & Wang, 2002, 2008; Maillet et al., 2017). White spruce relies heavily upon adequate soil moisture in the month of June. Predicted increases in June temperature with only small increases in June precipitation indicate that white spruce will suffer temperature induced drought during this time. Increases in July temperatures also have a large negative effect on white spruce growth, suggesting that summer temperatures will be too high under future climates for white spruce. In some small areas, white spruce growth is predicted to slightly increase. These increases are site specific and generally based off of one site's response to climate. As mentioned in the general chronology section of the Discussion, climate does not explain as much of the variance in white spruce ring-width, which could be because of the measures that are taken in southern Saskatchewan to keep white spruce alive. These measures include watering and other maintenance such as fertilizing throughout the growing season by the landowners, which likely breaks down the climate-growth relationship in white spruce. White spruce is not a good shelterbelt choice for landowners across the Brown, Dark Brown, and Black soil zones of Saskatchewan. If white spruce is chosen to be grown as a shelterbelt under future climates, it should be grown in the Black soil zone northward and will require a lot of watering.

6 SYNTHESIS AND CONCLUSIONS

Since producers began settling on the Saskatchewan prairies in the early 20th century, shelterbelts have been planted as a tool to reduce soil erosion and protect homes and crops from wind damage. The PFRA shelterbelt program at Indian Head distributed over 600 million shelterbelt seedlings to landowners across the Prairie provinces from 1963 to 2009 but were shut down in 2013, leaving many landowners upset and wondering where they were going to receive trees to continue upkeep and planting of shelterbelts (Rempel, 2014). The reasons behind the shutdown suggested that the shelterbelt program was outdated because new conservation tillage techniques reduced soil erosion and erased the need for shelterbelts, and shelterbelts are being taken out at an alarming rate because producers need space for their larger equipment (Agriculture and Agri-Food Canada, 2004). However, shelterbelts provide many more benefits than simply reducing soil erosion. Shelterbelts reduce pesticide drift, filter runoff and reduce pollutants in waterways, they have the potential to buffer the negative effects of climate change in agriculture by protecting crops and livestock from increasing severe weather events associated with climate change (ie. reducing crop lodging from wind and rain damage), and help to mitigate climate change by sequestering carbon (Gregory, 1995; Ucar & Hall, 2001; Wall & Smit, 2005; Ryszkowski & Kedziora, 2007; Trevino-Garrison et al., 2015).

The threat of climate change has motivated many researchers to study the effects of climate change on trees by predicting their growth into the future using tree-rings and future climate models (Phillips, 2009; Lapointe-Garant et al., 2010; Williams et al., 2010; Huang et al., 2013). Until now, no study to my knowledge had ever been conducted on how shelterbelts are predicted to grow and respond to climate change in Saskatchewan. The research presented here addressed this knowledge gap by predicting how four shelterbelt species will grow under future climate change conditions using dendrochronology techniques and future climate models. This information on predicted shelterbelt growth into the future is available for the public in a new computer application [shelterbelt-sk.ca] that includes a wide range of shelterbelt information on maintenance, carbon sequestration, shelterbelt design, recommending shelterbelt species for certain areas of Saskatchewan and more. The application is considered a decision support system for shelterbelts and was created by a team of people working on phase two of AGGP, and whose goal it was to create a management toolbox to help landowners and producers manage, plant, and maintain their shelterbelts. All of my research is already incorporated into this decision support system. This will help landowners choose a shelterbelt species that will grow successfully in their area of the province under climate change conditions and help to maximize the amount of carbon that the trees can sequester in the future under good growth environments.

6.1 Summary of Findings

Green ash growth is predicted to increase across most of south-central Saskatchewan, excluding areas in the more westerly areas of the province. The reason for this increase is mainly attributed to the predicted future increases in spring and June precipitation. Green ash is considered relatively drought tolerant and is adapted to southern Canada, which helps explain its tolerance to climate change induced arid conditions in Saskatchewan under future climate models. However, rising spring and summer temperatures in the more westerly areas of Saskatchewan will likely cause temperature-induced drought in green ash, resulting in predicted decreases in green ash growth in these areas. Despite this predicted decrease in the west, green ash is still relatively resilient to climate change in Saskatchewan because of its drought tolerance and could be a good choice for many landowners in southern Saskatchewan. Although, landowners should be careful when choosing green ash, because the EAB poses a serious threat to green ash shelterbelt stands (Government of Saskatchewan, 2017). The EAB has not currently been found in Saskatchewan but has the potential to spread to Saskatchewan and devastate green ash shelterbelts in the province.

Hybrid poplar growth is predicted to slightly decrease in the future. This decrease is slow to develop and is slight because the decreases in hybrid poplar radial growth that are caused by rising summer temperatures are counteracted by predicted increases in autumn precipitation which is positively related to hybrid poplar growth. If hybrid poplar is watered and maintained, it may be possible to keep hybrid poplar alive across most of southern Saskatchewan, because the predicted decreases in hybrid poplar growth are small. Generally, hybrid poplar needs more moisture in the late summer because they rely upon this late soil moisture to produce carbohydrate reserves to use for the following growth season.

Scots pine's main driver of growth is spring and summer (mainly June) precipitation, which partly accounts for the increases in Scots pine growth predicted growth in the westerly areas of southern Saskatchewan. The increase in Scots pine growth in the north is attributed to the positive impact that spring temperature has on Scots pine growth. Previous studies have found that past Scots pine growth is positively influenced by spring temperature, but this relationship is breaking down under warming climates, likely because higher temperatures disrupt the dehardening of trees (Jacoby and D'Arrigo, 1995; D'Arrigo et al., 2008; Misi et al., 2019). This concept is called divergence and could potentially be what we are seeing in the relative weights and predicted Scots pine growth maps (Figure 4.17), because only sites in the northwest corner of the study area are significantly and positively correlated to spring temperature, indicating that in colder climates this relationship is still present. The relationship between Scots pine growth and climate appear to be somewhat variable throughout the southern half of Saskatchewan, and it would be helpful to have more sites to describe this relationship and attempt to see more of a pattern in the relationship.

White spruce radial growth is predicted to mainly decrease across the Brown, Dark Brown, and Black soil zones of Saskatchewan. Adequate soil moisture during the month of June was found to be critical for white spruce growth. Predicted rising June temperatures along with only small increases in June precipitation will likely cause temperature-induced drought in white spruce, thus having a large negative effect on white spruce radial growth. Rising July temperatures also have a large negative effect on white spruce growth, indicating that summer temperatures will be too high for white spruce to grow successfully in the southern half of Saskatchewan. Many studies have come to the same conclusion, that the southern boundary of white spruce growth in moving northward, and as a result white spruce will not grow well in the three southernmost soil zones of Saskatchewan (Hogg and Schwarz, 1997; Chhin & Wang, 2002, 2008; Maillet et al., 2017).

6.2 Shelterbelt implications and recommendations

Shelterbelts are currently being taken out at an alarming rate, mainly because farmers need more room for larger equipment, and conservation tillage operations reduce the need for soil erosion protection from shelterbelts (Rempel, 2014). However, in dry years minimum tillage is often not enough to slow soil erosion, and shelterbelts provide many more benefits other than soil erosion protection. Climate change has the potential to have large negative effects on crops and livestock, and shelterbelts could help reduce some these negative effects by protecting crops and livestock from the elements and climate change induced severe weather events, providing much needed moisture through snow trapping in drought years and many more (Dickey, 1988; Wall and Smit, 2005). Shelterbelts also sequester carbon which helps to mitigate climate change. If carbon credits were given to landowners who keep and/or plant more shelterbelts, it would incentivize landowners to plant more shelterbelts, ultimately sequestering more carbon and further mitigating climate change. If the potential of carbon credits were realized, it is important that landowners have access to the information of what shelterbelts will grow best in their area under future climates and will therefore sequester the most carbon. This study provides maps of where different shelterbelt species are predicted to experience increases or decreases in growth and has recommendations of which shelterbelt may be best for a particular region in southern Saskatchewan. This information is made easily available for the public in the new shelterbelt application [shelterbelt-sk.ca].

Green ash appears to be more resilient to climate change in Saskatchewan than the other shelterbelt species in this study but should be planted with caution because of the risk of EAB spreading to Saskatchewan. Hybrid poplar could survive climate change conditions across most of southern Saskatchewan if the trees are watered and maintained. Since hybrid poplar relies heavily upon previous late summer and early fall moisture, it is important to water during these times. Scots pine could potentially grow well on the western and more northerly regions of southern Saskatchewan, but more research should be conducted on Scots pine since there were few sites collected across the study area, and the relationship between Scots pine and climate was highly variable. White spruce responds negatively to high summer temperatures, and as a result is not a good choice as a shelterbelt under future climate conditions in Saskatchewan. For more information on planting a new shelterbelt, shelterbelt maintenance, taking out shelterbelts, and estimates on carbon sequestration, landowners should visit the new shelterbelt application at shelterbelt-sk.ca.

6.3 Future Research Directions

Only four shelterbelt species were researched in this study, and there are many more common shelterbelts species in Saskatchewan whose growth could be predicted into the future. Shelterbelts such as Manitoba maple (*Acer negundo*), Colorado spruce (*Picea pungens*), willows (*Salix* spp.), American elm (*Ulmus americana*), and many more could be studied to determine their potential to thrive under future climate change conditions in Saskatchewan. More green ash, hybrid poplar, Scots pine, and white spruce sites could also be added to this research to make the data stronger and more reliable for landowners to use. This research could also be conducted in the Grey and Dark Grey soil zones since many producers also farm in this area. Research in these more northern soil zones may be more valuable to landowners if the study focused on native trees because shelterbelts in the area are often made up of strips of native forests left between fields or around homes quarters. Landowners living in the Grey and Dark Grey soil zones would likely benefit from research quantifying the amount of carbon stored in these natural shelterbelts. Also being able to compare the carbon potential and other benefits of a natural shelterbelt versus a planted shelterbelt, and are there any negative effects that non-native trees have as shelterbelts in the Gray and Dark Gray soil zones. These potential research ideas would fit well into the current computer application that serves to help landowners with their shelterbelts.More research could also be conducted on using a different type of model to produce a more accurate model to predict future growth. Other models often require more information, such as soil type, insect infestation, and in the case of shelterbelts, maintenance completed by the landowners. A model using a drought indices, an adaptive growth model, or a multimodel ensemble could strengthen future radial growth predictions.

Further research into mixed species shelterbelts, and if a biodiverse shelterbelt is be more resilient to climate change. Do these more diverse shelterbelts have greater benefits than single species shelterbelts, and what are these benefits? Do the benefits of these multi-species shelterbelts, make up for cost and larger area that they take up. More research could be conducted on shelterbelts in a more ecological aspect for both farms and native prairie and parkland areas.

Shelterbelts are often watered, fertilized, and maintained by landowners, which can alter the trees' ability to survive in the area. To what extent will maintenance continue to keep a tree alive? What maintenance is needed to keep white spruce alive under future climate change conditions in southern Saskatchewan? Is it possible to keep ill adapted trees alive with maintenance, and is there a threshold where even continued maintenance will not keep them alive? These are all important questions that should be answered in order to help landowners keep their trees alive and give them more options of shelterbelt trees to plant.

If shelterbelts were recognized as a carbon credit for producers and landowners, it would provide an incentive to keep shelterbelts and plant new ones. This research predicting future growth of shelterbelt trees could help to estimate the amount of carbon that will be sequestered and help to maximize future carbon credits for landowners. Not only does it have great potential for landowner use, policy makers could also gain a lot from this research and the shelterbelt decision support system.

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8 APPENDICES

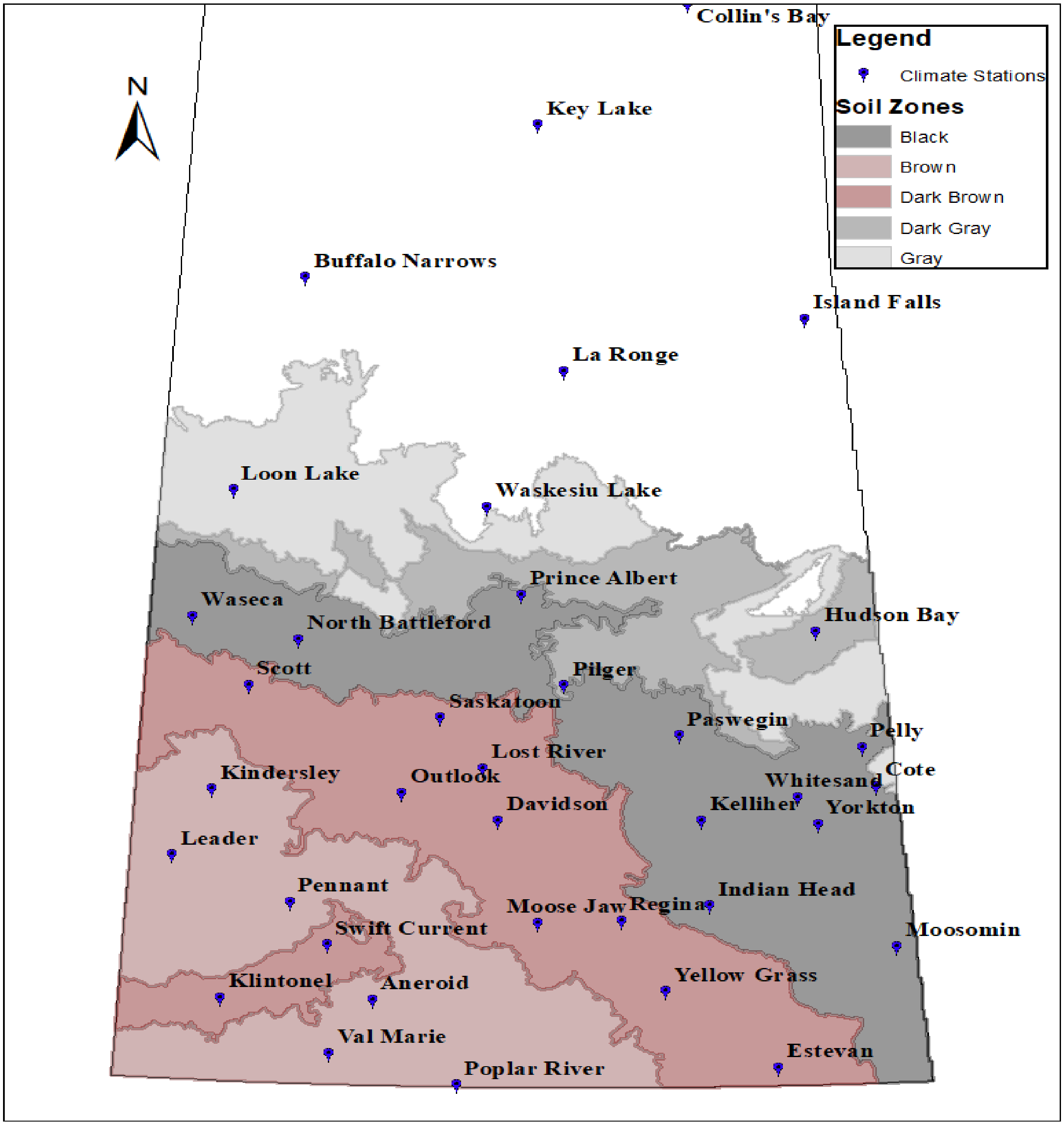

Figure A.1 Locations of the climate stations across the southern half of Saskatchewan. Past temperature and precipitation climate data was used from these climate stations. ArcMap 10.7.

Table A.1 The number of trees sampled from and the number of cores analyzed at each site. The climate station that provided the past climate data for each site.

Species	Site Name	Number of trees	Number of cores	Climate station
Green ash	15BLM00	20	40	Davidson
Green ash	15DLM00	20	39	Davidson
Green ash	14XLM00	20	40	Outlook
Green ash	14PLM00	20	40	Saskatoon
Green ash	14MLM00	20	40	Saskatoon
Green ash	14ILM00	20	40	Kindersley
Green ash	14BILM00	20	40	Waseca
Green ash	14BALM00	20	40	Pennant
Green ash	18ILM00	18	36	Indian Head
Green ash	18TLM00	20	39	Aneroid
Green ash	12JLM00	20	40	Estevan
Green ash	12QLM00	20	40	Indian Head
Green ash	11ALLM00	20	40	Moose Jaw
Green ash	18RLM00	18	35	Swift Current
Green ash	13CLM00	20	40	Outlook
Green ash	18MLM00	20	39	Yorkton
Green ash	11AILM00	17	33	Regina
Green ash	13LLM00	20	39	Kelliher
Green ash	12AGLM00	20	40	Kelliher
Green ash	12KLM00	20	40	Estevan
Green ash	12PLM00	20	40	Kelliher
Green ash	18QLM00	18	36	Pennant
Green ash	11AMLM00	20	40	Davidson
Hybrid poplar	14BBLN00	28	55	Aneroid
Hybrid poplar	14KLN00	18	36	Swift Current
Hybrid poplar	18YLN00	16	32	Outlook
Hybrid poplar	11MLN00	19	37	Saskatoon
Hybrid poplar	13ILN00	17	33	Paswegin
Hybrid poplar	14HLN00	20	40	Scott
Hybrid poplar	14BDLN00	17	34	Saskatoon
Hybrid poplar	14BELN00	20	40	Pilger
Hybrid poplar	18DLN00	19	37	Waseca
Scots pine	11DLS00	17	33	Prince Albert
Scots pine	11ILS00	17	33	Saskatoon
Scots pine	18CLS00	16	32	Whitesand
Scots pine	13PLS00	21	41	Pilger
Scots pine	14SLS00	18	36	Indian Head
Scots pine	14PLS00	19	38	Saskatoon

Scots pine	14YLS00	20	40	Outlook
Scots pine	17PLS00	20	39	Moose Jaw
Scots pine	18ZLS00	18	36	Regina
Scots pine	18PLS00	18	35	Pennant
Scots pine	18WLS00	17	34	Scott
Scots pine	14BCLS00	18	36	Saskatoon
Scots pine	18XLS00	18	36	Kindersley
White spruce	12AEL200	19	38	Estevan
White spruce	18VL200	18	36	Aneroid
White spruce	18KL200	18	35	Moosomin
White spruce	12ML200	20	40	Yellow Grass
White spruce	18SL200	15	30	Klintonel
White spruce	17HL200	19	38	Swift Current
White spruce	12AAL200	20	39	Swift Current
White spruce	12ACL200	20	40	Moose Jaw
White spruce	11ANL200	20	39	Swift Current
White spruce	12QL200	20	40	Indian Head
White spruce	17DL200	20	39	Moose Jaw
White spruce	11ADL200	20	40	Indian Head
White spruce	12AHL200	20	40	Yorkton
White spruce	12NL200	20	40	Kelliher
White spruce	12ANL200	20	40	Outlook
White spruce	15BL200	20	41	Davidson
White spruce	12AIL200	20	39	Whitesand
White spruce	17CL200	20	40	Kindersley
White spruce	12OL200	19	38	Paswegin
White spruce	12GL200	19	38	Paswegin
White spruce	11JL200	20	40	Saskatoon
White spruce	11GL200	19	38	North Battleford
White spruce	11DL200	19	38	Prince Albert

R Script A.1 The basic R code used for each site and set of tree cores to determine their predicted future growth.

```
#The purpose of this script is to:
#Create a linear growth model, determine the relative imporances of the variables
#Cross validate results, graphically display results, run a t-test to see if there is a statistical difference between time periods
###LAST UPDATE: February 22, 2019 (ELD) -----------------


rm(list=ls()) #Remove all files from R


#Setting Working Directory and importing data (white spruce example)
setwd("~/Desktop/Example Data")
sample <- read.csv("~/Desktop/Example Data/Ex_Historical.csv")


#Load packages
packs <- c('MASS','ggplot2','ggthemes','dplyr', 'bootstrap', 'broom') lapply(packs, library, character.only = TRUE)


#Creating preliminary models for each 'type' of monthly variable


#Current Temperature Model (in this example, C_AprT represents current April temperautre)
mod1<-lm(Ring.Width~C_AprT+C_MayT+C_JunT+C_JulyT+C_AugT+C_SeptT, data = sample) %>% stepAIC(.)

#summary(mod1) #Current Precip
mod2<-lm(Ring.Width~C_AprP+C_MayP+C_JunP+C_JulP+C_AugP+C_SeptP, data = sample)%>% stepAIC(.)

#summary(mod2) #Prev Temp
mod3<-lm(Ring.Width~P_AprT+P_MayT+P_JunT+P_JulyT+P_AugT+P_SeptT, data = sample)%>% stepAIC(.)

#summary(mod3) #Prev Precip
mod4<-lm(Ring.Width~P_AprP+P_MayP+P_JunP+P_JulP+P_AugP+P_SeptP, data = sample)%>% stepAIC(.)
```

```
#summary(mod4)

#Making a final optimized model
#Extracting variable names from the four models v.mod1<-variable.names(mod1)
v.mod2<-variable.names(mod2)                v.mod3<-variable.names(mod3)                v.mod4<-
variable.names(mod4)

#Creating a character string with sig. variables
var.names <- c(v.mod1[-1], v.mod2[-1], v.mod3[-1], v.mod4[-1]) var.names

#A preliminary final model #Specifying the lm formulat
mod.eq <- paste(names(sample)[2], "~", paste(var.names, collapse=" + "))

#Running model and performing stepAIC mod5<-lm(mod.eq, data = sample) %>%
stepAIC(.)

#CANDIDATE final model: check for insignificant climate variables; remove in next step
summary(mod5)

#mod5 demonstrated that P_AugP is not 'significant' and so it is eliminated from final model
mod5<-update(mod5,~.-P_AugP) summary(mod5) #THIS IS FINAL MODEL

#MODEL VALUES (if needed)
mod.coeff <- summary(mod5)$coefficients[,1] #Coefficients of modelvariables mod.pval <-
summary(mod5)$coefficients[,4] #p.vals of model variables mod.sum <- glance(mod5) #model
summary

#Use "write.csv(object, 'filename.csv')" to save this information outside of R

#Evaluating Model Fit par(mfrow=c(2,2)) plot(mod5, which=c(1:4))
```

```
par(mfrow=c(1,1))


#Check for collinearity library(faraway) vif(mod5)


###FUTURE GROWTH FORECASTING ----------------------
#Read in all 6 future scenarios
rpc45.can <- read.csv("~/Desktop/Example Data/Ex_Future.csv") #rpc45.crm <- x #CHANGE
#rpc45.inm <- x #CHANGE #rpc85.can <- x #CHANGE #rpc85.crm <- x #CHANGE #rpc85.inm
<- x #CHANGE


rpc45.can<- as.data.frame(cbind(rpc45.can[1],predict(mod5, rpc45.can))) %>% rename(.,
   Ring.Width = 2) %>%
mutate(TimeFrame = 'Future', Scenario = 'RPC 45 can')
#RUN THIS CODE when you have the other five scenarios ready
# rpc45.crm<- as.data.frame(cbind(rpc45.crm[1],predict(mod5, rpc45.crm))) %>% #
        rename(., Ring.Width = 2) %>%
#       mutate(TimeFrame = 'Future',
#               Scenario = 'RPC 45 crm') #
# rpc45.inm<- as.data.frame(cbind(rpc45.inm[1],predict(mod5, rpc45.inm))) %>% #
        rename(., Ring.Width = 2) %>%
#       mutate(TimeFrame = 'Future',
#               Scenario = 'RPC 45 inm') #
# rpc85.can<- as.data.frame(cbind(rpc85.can[1],predict(mod5, rpc85.can))) %>% #
        rename(., Ring.Width = 2) %>%
#       mutate(TimeFrame = 'Future',
#               Scenario = 'RPC 85 can') #
# rpc85.crm<- as.data.frame(cbind(rpc85.crm[1],predict(mod5, rpc85.crm))) %>% #
        rename(., Ring.Width = 2) %>%
#       mutate(TimeFrame = 'Future',
#               Scenario = 'RPC 85 crm') #
# rpc85.inm<- as.data.frame(cbind(rpc85.inm[1],predict(mod5, rpc85.inm))) %>% #
        rename(., Ring.Width = 2) %>%
#       mutate(TimeFrame = 'Future',
#               Scenario = 'RPC 85 inm')


#Creating a dataframe with historical growth
hist.growth <- cbind(sample[1:2], "TimeFrame" = c('Historical'), "Scenario"= c('Actual'))
```

```
#Creating a dataframe with historical predicted growth hist.pred <-
as.data.frame(cbind(sample[1],predict(mod5))) %>%
rename(., Ring.Width = 2) %>% mutate(TimeFrame = 'Historical',
Scenario = 'Historical predicted')



#Combining past and future growth together
all.growth <- rbind(hist.pred, hist.growth, rpc45.can)



#RUN THIS CODE INSTEAD when you have all 6 scenarios
# all.growth <- rbind(hist.pred, hist.growth, rpc45.can, rpc45.crm, rpc45.inm, rpc85.can,
rpc85.crm, rpc85.inm)



#PLOTTING past and future growth ------------------------
growth.plot <- ggplot(all.growth,
                              aes(x=Year, y=Ring.Width, color = Scenario))+
geom_path(aes(linetype=Scenario))+
  scale_colour_manual(values = c('black', 'blue','red', 'green', 'purple', 'pink', 'yellow', 'grey'))+
#May want to change these colours, or delete this line of code and use default
theme_bw()+ xlab('Year')+
ylab('Standardized ring width')+ ggtitle('Title of this plot')



growth.plot
```

```
#The next line of code saves your plot to the working directory - specify the plot name, and play around with the dimensions to get the size you want ggsave(plot=growth.plot,
"PLOTNAME.pdf", device = "pdf", width = 6.5, height
= 4.75, units = c("in"), dpi= 600)
```

```
#Conducting a t-test to determine if there is a sig. difference between past/forecasted
test1 <- t.test(hist.growth$Ring.Width, rpc45.can$Ring.Width, alternative =
c("two.sided"), paired = FALSE, var.equal = FALSE)
```

```
#Use these lines to run t-tests for other scenarios
# test2 <- t.test(hist.growth$Ring.Width, rpc45.crm$Ring.Width, alternative =c("two.sided"),
paired = FALSE, var.equal = FALSE)
#
# test3 <- t.test(hist.growth$Ring.Width, rpc45.inm$Ring.Width, alternative =c("two.sided"),
paired = FALSE, var.equal = FALSE)
#
# test4 <- t.test(hist.growth$Ring.Width, rpc85.can$Ring.Width, alternative =c("two.sided"),
paired = FALSE, var.equal = FALSE)
#
# test5 <- t.test(hist.growth$Ring.Width, rpc85.crm$Ring.Width, alternative =c("two.sided"),
paired = FALSE, var.equal = FALSE)
#
# test6 <- t.test(hist.growth$Ring.Width, rpc85.inm$Ring.Width, alternative =c("two.sided"),
paired = FALSE, var.equal = FALSE)
```

```
#You can save results of t-tests to a dataframe
vars <- c('statistic', 'parameter', 'p.value', 'data.name')
```

```
test.results<-as.data.frame(rbind(test1[vars], test2[vars])) #...Add tests in as needed


#Relative weights method from Kabacoff (2011)
#A method of demonstrating which variables are most important/influential #Creates graphical
representation of relative importances
relweights <- function(fit,...){ R <- cor(fit$model) nvar <- ncol(R)
rxx <- R[2:nvar, 2:nvar] rxy <- R[2:nvar, 1]
svd <- eigen(rxx) evec <- svd$vectors ev <- svd$values
delta <- diag(sqrt(ev))
lambda <- evec %*% delta %*% t(evec) lambdasq <- lambda ^ 2
beta <- solve(lambda) %*% rxy rsquare <- colSums(beta ^ 2) rawwgt <- lambdasq %*% beta ^
2 import <- (rawwgt / rsquare) * 100 lbls <- names(fit$model[2:nvar]) rownames(import) <- lbls
colnames(import) <- "Weights"
barplot(t(import),names.arg=lbls,ylab="% of R-Square", xlab="Predictor Variables",
main="Relative Importance of Predictor Variables", sub=paste("R- Square=", round(rsquare,
digits=3)), ...)
return(import)}
relweights(mod5)
#Cross Validation Procedure using 'shrinkage' function (described in Kabacoff, 2011)
#Creating a function 'shrinkage' shrinkage <- function(fit, k){


require(bootstrap)
theta.fit <- function(x,y){lsfit(x,y)}
theta.predict <- function(fit,x){cbind(1,x)%*%fit$coef}


x<-fit$model[,2:ncol(fit$model)] y<-fit$model[,1]
results <- crossval(x, y, theta.fit, theta.predict, ngroup=k) r2<-cor(y, fit$fitted.values)^2
r2cv<-cor(y, results$cv.fit)^2 cat("Original R-square =", r2, "\n")
```

```
cat(k, "Fold Cross-Validated R-square =", r2cv, "\n") cat("Change =", r2-r2cv, "\n")
}



shrinkage(mod5, 10)
```

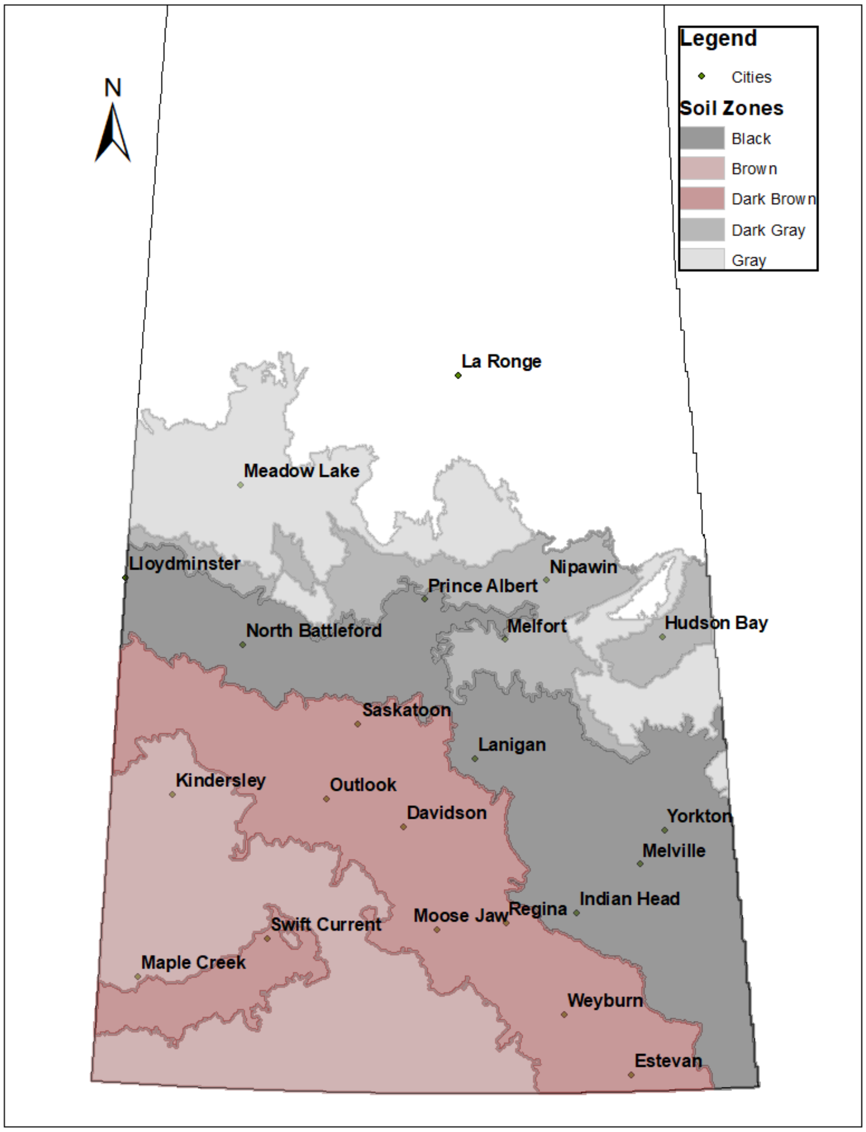

Figure A.2 Some of the cities located throughout the southern half of Saskatchewan that was mentioned in the text. ArcMap 10.7.