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Quantifying the Effects of Climate on the Radial Growth Rates of Urban Trees in Toronto

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Geography and Environment

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Abstract

Despite the importance of trees to urban ecosystem services and citizens' well-being, they are an understudied aspect of modern ecology. Although some studies have been conducted in other countries, no urban dendroclimatological work has been conducted in Canada. I investigated the impact of climate on urban tree growth, focusing on Toronto. I collected cores from five tree species: red oak, European linden, sugar maple, Norway maple, and Austrian pine, from street and park locations. I found a difference in environmental stress by location and by species, with street trees exhibiting negative correlations between summer temperature and growth. Norway maple and sugar maple were found to be particularly stressed by summer temperatures, with increases in negative growth-climate correlations in recent years, while red oak and linden were found to be less stressed by climate. An analysis of growth figures found high annual growth rates for both red oak and linden, and low annual growth for Norway maple and Austrian pine. This suggests that certain species may experience decreased growth rates in the coming decades due to climate change. The findings emphasize the need for attention to urban tree management in the face of changing climates, providing insights for urban forestry planning and conservation.

Keywords

Dendroclimatology, urban forestry, climate change, urban ecology, forest ecology, dendrochronology, biogeography, urban heat island

Summary for Lay Audience

This research investigated the impacts of the urban environment and climate on urban trees of the City of Toronto. Five species were sampled: red oak, European linden, sugar maple, Norway maple, and Austrian pine. Tree cores were collected from trees growing in both street and park locations in the city. To answer my research question, I measured the radial growth (tree-rings) of the sampled species and compared the growth to monthly climate variables (temperature and precipitation), as well as by calculating growth rates of the trees. My research found a difference in tree growth by both tree species and growing location (street vs. park), with street trees generally having lower growth rates. I have also found that the two sampled maple species, Norway and sugar maple, are increasingly stressed by high summer temperatures, while red oak and linden had higher overall growth rates and appeared less stressed by temperature. Species' response to precipitation varied, but linden and red oak were found to be more tolerant of precipitation shifts than other species. Red oak and linden also had high annual growth rates. This research indicates that some species in Toronto's urban forest may become more stressed in the future.

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Table of Contents

Abstract.....	ii
Keywords	ii
Summary for Lay Audience.....	iii
Acknowledgements.....	iv
Chapter 1 : Introduction and Background.....	1
1.1 Introduction.....	1
1.2 Background	3
1.2.1 Urban Trees.....	3
1.2.2 Urban Environment’s Impact on Trees.....	3
1.2.3 Urban Tree’s Impacts on Environment.....	6
1.3 Dendroclimatology.....	7
1.4 Urban Heat Island.....	8
1.5 Eastern North American Forests	8
1.5.1 Current Growth Patterns in Eastern North American Forests	8
1.5.2 Projected Growth Patterns in Eastern North American Forests	9
1.6 Sampled Species.....	11
1.6.1 Red Oak	11
1.6.2 Norway Maple	12
1.6.3 Sugar Maple.....	12
1.6.4 Linden.....	13
1.6.5 Austrian Pine.....	14
1.7 Literature Review Conclusions	14
1.8 Research Question and Objectives.....	15
Chapter 2 : Methods.....	16
2.1 Study Sites.....	16
2.1.1 Sampled Parks	22
2.1.2 Sampled Streets	24
2.2 Field Sampling Methods	25
2.3 Laboratory Methods	25

2.4 Analytical Methods	26
2.4.1 Cross-Dating	26
2.4.2 Detrending	27
2.4.3 Climate Data	28
2.4.4 Climate/Growth Correlations and Statistical Limitations	28
2.4.5 Basal Area Index (BAI)	29
2.4.6 BAI Segmented Breakpoint Regressions	30
Chapter 3 : Results	32
3.1 Introduction	32
3.2 Static and Moving Dendroclimatological Analyses	33
3.2.1 Static Precipitation Analysis	33
3.2.2 Static Temperature Analyses	35
3.2.3 Moving Precipitation Analysis	36
3.2.4 Moving Temperature Analysis	48
3.3 BAI Analysis	59
3.3.1 All Trees BAI	59
3.3.2 Segmented BAI Analysis	60
3.4 General Patterns	65
Chapter 4 : Discussion	68
4.1 Species/Growth Trends	68
4.1.1 Linden	68
4.1.2 Red Oak	70
4.1.3 Austrian Pine	71
4.1.4 Sugar Maple	73
4.1.5 Norway Maple	74
4.2 Potential Future Changes	75
4.2.1 Trees Well-Adapted to Toronto's Urban Climate	75
4.2.2 Species Tolerant to Toronto's Urban Climate	76
4.2.3 Species Poorly Suited for Toronto's Urban Climate	77
4.2.4 Study Limitations and Future Research	77
Chapter 5 : Conclusion and Management Recommendations	80
5.1 Conclusion	80

5.2 Management Recommendations	81
5.2.1 Management Recommendations – Other Suitable Species	81
5.2.2 Planting Recommendations – Sampled Species	82
Bibliography	84
Appendix.....	103

List of Figures

Figure 2.1: Climograph for the city of Toronto with data from 1900-2023	17
Figure 2.2: The ten most abundant species of street trees in Toronto as a percentage of total street tree population.	18
Figure 2.3: Sampled Toronto parks. 5 parks in total were sampled.	21
Figure 2.4: Sampled Toronto Street Trees Locations. 20 street locations were sampled in total.....	22
Figure 2.5: Flowchart of laboratory and analytical methods.	25
Figure 2.6: An example of segmented linear regression model.	30
Figure 3.1: Moving climate correlations for park linden radial growth and monthly total precipitation....	38
Figure 3.2: Moving climate correlations for street linden radial growth and monthly total precipitation. .	39
Figure 3.3: Moving climate correlations for park Norway maple radial growth and monthly total precipitation.	40
Figure 3.4: Moving climate correlations for street Norway maple radial growth and monthly total precipitation.	41
Figure 3.5: Moving climate graph for park red oak and monthly mean precipitation.	42
Figure 3.6: Moving climate graph for street red oak and monthly mean precipitation.....	43
Figure 3.7: Moving climate graph for park Austrian pine and monthly mean precipitation.....	44
Figure 3.8: Moving climate graph for street Austrian pine and monthly mean precipitation.	45
Figure 3.9: Moving climate graph for park sugar maple and monthly mean precipitation.....	46
Figure 3.10: Figure Moving climate graph for street sugar maple and monthly mean precipitation.....	47
Figure 3.11: Moving climate graph for park linden and monthly mean temperature.	49
Figure 3.12: Moving climate graph for street linden and monthly mean temperature.....	50
Figure 3.13: Figure Moving climate graph for park Norway maple and monthly mean temperature.	51
Figure 3.14: Figure Moving climate graph for street Norway maple and monthly mean temperature.....	52
Figure 3.15: Moving climate graph for park red oak and monthly mean temperature.	53
Figure 3.16: Moving climate graph for street red oak and monthly mean temperature.....	54
Figure 3.17: Moving climate graph for park Austrian pine and monthly mean temperature.....	55
Figure 3.18: Moving climate graph for street Austrian pine and monthly mean temperature.	56
Figure 3.19: Figure Moving climate graph for park sugar maple and monthly mean temperature.	57
Figure 3.20: Moving climate graph for street sugar maple and monthly mean temperature.	58
Figure 3.21: Plot of all species and locations average BAI growth per year in mm.....	60
Figure 3.22: Segmented regression plot of linden.	61
Figure 3.23: Segmented regression plot of Norway maple.....	62
Figure 3.24: Segmented regression plot of red oak.....	63
Figure 3.25: Segmented regression plot of Austrian pine.	64
Figure 3.26: Segmented regression plot of sugar maple.	65

List of Tables

Table 2.1: Sampled locations and number of each species collected from listed location.....	20
Table 2.2: Sampled species by site with associated dendrochronological statistics.	28
Table 3.1: Metrics for each chronology used in the study.....	32
Table 3.2: Static climate correlations for radial tree growth and precipitation from May of the previous year to October of the current year.....	34
Table 3.3: Static climate correlations for radial tree growth and temperature from May of the previous year to October of the current year.....	36
Table 3.4: Summary table of moving precipitation climate-growth analysis.....	48
Table 3.5: Summary table of moving temperature climate-growth analysis.....	58

Appendix

Appendix Figure 1: RWI and sample depth for park linden	103
Appendix Figure 2: Precipitation static correlation plot for park linden.	103
Appendix Figure 3: Temperature static correlation plot for park linden.....	104
Appendix Figure 4: RWI and sample depth for street linden.....	105
Appendix Figure 5: Precipitation static correlation plot for street linden.....	106
Appendix Figure 6: Temperature static correlation plot for street linden.	106
Appendix Figure 7: RWI and sample depth for park Norway maple.	107
Appendix Figure 8: Precipitation static correlation plot for park Norway maple.....	108
Appendix Figure 9: Temperature static correlation plot for park Norway maple.	108
Appendix Figure 10: RWI and sample depth for street Norway maple.	109
Appendix Figure 11: Precipitation static correlation plot for street Norway maple.	109
Appendix Figure 12: Temperature static correlation plot for street Norway maple.	110
Appendix Figure 13: RWI and sample depth for park red oak.	110
Appendix Figure 14: Precipitation static correlation plot for park red oak.	111
Appendix Figure 15: Temperature static correlation plot for park red oak.....	111
Appendix Figure 16: RWI and sample depth for street red oak.....	112
Appendix Figure 17: Precipitation static plot for street red oak.	112
Appendix Figure 18: Temperature static plot for street red oak.	113
Appendix Figure 19: RWI and sample depth for park Austrian pine.....	113
Appendix Figure 20: Precipitation static correlation plot for park Austrian pine.	114
Appendix Figure 21: Temperature static correlation plot for park Austrian pine.	114
Appendix Figure 22: RWI and sample depth for street Austrian pine.	115
Appendix Figure 23: Precipitation static correlation plot for street Austrian pine.	116
Appendix Figure 24: Temperature static correlation plot for street Austrian pine.....	116
Appendix Figure 25: RWI and sample depth for park sugar maple.....	117
Appendix Figure 26: Precipitation static correlation plot for park sugar maple.	118
Appendix Figure 27: Temperature static correlation plot for park sugar maple.	118
Appendix Figure 28: RWI and sample depth for street sugar maple.	119
Appendix Figure 29: Precipitation static correlation plot for street sugar maple.	119
Appendix Figure 30: Temperature static correlation plot for street sugar maple.....	120

Chapter 1 : Introduction and Background

1.1 Introduction

Trees and forests worldwide are being exposed to new stressors because of anthropogenic climate change, such as increased heat stress, changing precipitation patterns, increased forest fire frequency and intensity, and insect infestations (Bishop et al., 2015; Bonney & He, 2021; Champagne et al., 2019; D'Arrigo et al., 2008; De Jaegere et al., 2016; Liebhold et al., 1995). Urban trees are particularly vulnerable to climate change, as the urban heat island (UHI) warms cities more than the surrounding rural and natural ecosystems, which could amplify the effects of the changing climate in cities (Pretzsch et al., 2017; Yang et al., 2016). Further, urban trees are exposed to a wide range of anthropogenic stressors unique to their growing environment, such as increased air pollution in urban areas, the use of road salts, and tree pruning (Gillner et al., 2014; Gülten et al., 2016; Moser et al., 2016). The study of the effects of climate change through rising global temperatures, changes in precipitation patterns, and increases in severe weather events and their effects on urban forests is a new and developing field. To date, several studies evaluating radial growth rates (tree-rings) using dendroclimatological methods have been conducted in some cities, mostly in Europe (Cedro & Nowak, 2006; Dahlhausen et al., 2018; Schneider et al., 2022), with fewer urban dendroclimatological studies elsewhere.

Dendroclimatology (the use of tree rings to study the relationships between tree growth and climate and climate changes) can be used to quantify the effects of urban climate on radial tree growth through quantifying annual ring-width growth measurements and correlating this growth to monthly climate variables. This analysis can provide insight into the climate variables controlling tree growth, the overall growth trends of urban tree species, and inform predictions of future growth (Dahlhausen et al., 2018; Speer, 2010). The handful of studies that have been

conducted to date suggest that the urban environment combined with climate change is causing increased physiological stress (i.e., reduced radial growth) for some urban tree species (e.g. Kjelgren & Clark, 1992; Moser et al., 2016; Moser-Reischl et al., 2019), while other tree species are exhibiting enhanced radial growth (e.g. Dahlhausen et al., 2018; Pretzsch et al., 2017; Schneider et al., 2022). Species that are experiencing reduced radial growth may be due to factors unrelated to climate change, such as having low pollution or shade tolerances (Moser-Reischl et al., 2019) or the species may in fact be experiencing increased stress from the changing climate, such as having a low tolerance to increased summer temperatures (David et al., 2018; Zimmermann et al., 2015). Trees may experience enhanced growth for similar reasons, as some studies have shown faster growth in urban tree species from increased concentrations of CO₂ (Dahlhausen et al., 2018; Pretzsch et al., 2017), while other species may experience an increase in growth due to the changing climate bringing more favorable climates for that species in the city (Pretzsch et al., 2017). However, dendroclimatological research needs to be conducted in the local context (using local climate parameters and growth data from local trees), studies from other regions/continents can be of limited value as the tree species and climate differ greatly, though such studies can still inform on general trends and patterns.

The broad objectives of this thesis are to quantify the effects of urban climate on the radial tree growth rates of commonly planted tree species in the City of Toronto in order to: better understand the climate-growth relationships of Toronto's urban forest, to evaluate difference between growing locations within the city (street and park), and to provide recommendations to the city on what species are the best suited for future planting within the city.

1.2 Background

1.2.1 Urban Trees

There has been limited research on the effects of urban climate on radial tree growth. Much of the prior research on urban tree growth has examined ways in which urban trees affect the urban environment, not how the environment impacts the trees. While the focus of this study is on the impact of urban climate on trees, studies into the effects of trees on urban environment can still yield important insight into urban environmental dynamics. Previous studies into urban trees' impact on urban environments will be explored herein, as well as research conducted on how urban environments impact tree growth.

1.2.2 Urban Environment's Impact on Trees

Whilst fewer in number, studies conducted on the impact of urban environments on tree growth have shown that generally most trees exhibit physiological stress due to the effects of climate change and the urban heat island (Cedro & Nowak, 2006; Dahlhausen et al., 2018; Schneider et al., 2022). Within Berlin, Germany, tree species exhibited high levels of physiological stress in more developed areas, and that urban tree growth was related to the urbanity index (UI), a measure of urbanization in cities based on development levels, with higher UI values correlating to higher stress (i.e., lower growth) in trees (Schneider et al., 2022). A study conducted in Berlin found that some species exhibited enhanced growth in highly dense urban areas, but that the same tree species were stressed in areas of medium density (Dahlhausen et al., 2018). This increase in growth was hypothesized to have been caused by elevated CO₂ levels in more developed areas, and that lower growth in medium density areas was due to a debris and pollution from construction (Dahlhausen et al., 2018). The finding that areas with higher levels of construction had lower growth could have important implications for cities in

Canada and southern Ontario, as Toronto and the GTA is a rapidly growing and developing area (Government of Canada, 2022).

A comprehensive review of urban tree research found that many species exhibit accelerated growth in urban environments, which is likely attributed to elevated levels of CO₂ in urban areas (Pretzsh et al., 2017). White oak (*Quercus alba*) and red maple (*Acer rubrum*) were found to exhibit accelerated growth patterns in eastern cities in the United States, and that older specimens demonstrated increasing growth with age, suggesting a level of acclimation to urban environments (Sonti et al., 2019). However, these benefits may subside as cities continue to experience increased temperatures. As temperatures continue to warm worldwide, trees may go from benefitting from warmer air temperatures to being stressed by them, as higher temperatures can cause moisture and heat stress in many common urban tree species (Pretzsch et al., 2017). This problem could be particularly pronounced in species not in their natural range or that have had their range shift due to climate changes, a problem that could become pronounced in cities due to the larger number of planted non-native species in urban areas (Pretzsch et al., 2017; Schlaepfer et al., 2020).

Urban trees' growth patterns are also highly localized, with differences in growth patterns found between the same species in different urban growing environments (street and park) (Lv et al., 2024; North et al., 2018). Street Norway maples were found to have a lower leaf area than park trees of the same species in a study in Karlsruhe, Germany (Lv et al., 2024) while the DBH of street trees in Minneapolis, Minnesota were found to be larger than those of their park counterparts (North et al., 2018). These studies, along with differing results from cities within close proximity to each other in Europe, such as declines in oak growth rates in Helsinki, Finland (Helama et al., 2009) yet increases in little-leaved lime growth in Berlin, Germany (Dahlhausen

et al., 2018) suggest that urban tree growth is not only highly localized to the city and species, but to different growing environments within the city.

Urban pollution and chemicals can also play a role in tree growth and health (Equiza et al., 2017; Locosselli et al., 2019; Ordonez-Barona et al., 2018), such as the use of road salts in winter (Equiza et al., 2017). Soil pH has been found to be elevated in roadside growth areas, which can negatively impact the availability of essential nutrients for tree growth as well as disrupt and limit necessary soil biota (Equiza et al., 2017; Ordonez-Barona et al., 2018). High traffic areas are the most negatively affected, possibly due to enhanced road salt use on high traffic roads as well as the greater chance of vehicles and plows spraying or pushing salt to the side of roads and into tree plots and street-side parks (Equiza et al., 2017). Certain tree species have also been found to be more susceptible to road salt induced stress, such as American elm (*Ulmus americana*), while green ash (*Fraxinus pennsylvanica*) has been found to be relatively salinity resistant (Equiza et al., 2017). The planting of salinity-resistant species would be particularly important in Canadian and other northern cities, as road salts and other de-icing methods are common and could be stressing dormant trees (Equiza et al., 2017; Nassiri et al., 2015).

While several studies have established a positive relationship between elevated CO₂ levels and tree growth (Dahlhausen et al., 2018; Pretzsch et al., 2017), other types of urban pollution may negatively impact tree growth. Industry related airborne particulate matter (PM₁₀) may reduce tree growth by up to 37% if pollution concentrations are high (0.50–0.80 µg/m³) (Locosselli et al., 2019). However, trees may experience increased growth if exposed to phosphorus deposition, given that phosphorus is an essential element to tree growth and has limited natural production in urban environments (Locosselli et al., 2019). Other studies have

also identified nitrogen dioxide (NO₂) emissions as having a positive impact on tree growth, likely due to the limited number of nitrogen-fixing plants found in urban ecosystems, however these emissions can also cause increased growth of unwanted species, such as toxic algal blooms in some areas (Moser-Reischl et al., 2019).

1.2.3 Urban Tree's Impacts on Environment

Previous research has yielded important insights into urban forest mechanics and the benefit they provide to cities. Urban trees increase inhabitant's enjoyment of the environment and quality of life, with urban areas with greenery reporting happier residents (Mullaney et al., 2015). Residents reported greater levels of aesthetic value of their neighborhoods as well as feelings of increased safety with the presence of street trees due to the additional barrier between pedestrians and vehicles (Mullaney et al., 2015). Urban trees are also correlated with economic benefits, with one study in Los Angeles, California suggesting a potential benefit of USD \$1,000 worth of aesthetic value, environmental services, and energy savings per tree to the local economy (McPherson et al., 2011).

In addition to improving the quality of life and providing economic benefits, urban trees have been found to provide additional key ecosystem services to cities worldwide. Urban trees in the United States have been associated with removing 10.8 g m⁻² a⁻¹ (pollution removal value per unit canopy cover) of pollutants from urban air (Nowak et al., 2006). Urban trees have also been shown to assist in reducing runoff and increase rainfall interception, with one study finding that urban trees can reduce runoff by up to 62%, preventing runoff from carrying urban pollutants to drainage channels (Armson et al., 2013).

Urban trees also provide important shading services to cities worldwide, as urban trees can help moderate the elevated temperatures in cities caused by the UHI (Zhou et al., 2017).

Urban trees reduce heat through cooling associated with evapotranspiration, as well as by their canopies preventing incoming solar radiation from reaching urban surfaces, such as roads, sidewalks, and buildings (Armson et al., 2012; Soledad Duval et al., 2020). Cities with high urban tree cover have been found to be cooler in the face of warm summer temperatures, with trees helping to cool the surrounding built environment by up to 7 °C (Spronken-Smith & Oke, 1998). Large city parks have been found to have the most impact on cooling, specifically parks that have large areas of grass coverage, as large grassy areas can cool cities by absorbing solar radiation with trees providing shading and evapotranspiration (Armson et al., 2012). Tree coverage of any kind can help to create cooler microclimates within cities, providing cooler air temperatures to alleviate the effects of the UHI and climate-change induced warmer temperatures for city inhabitants (Soledad Duval et al., 2020).

1.3 Dendroclimatology

Dendrochronology as a field is the study of tree rings to inform on past, current, and future climates, growth, and events (Speer, 2010). Dendroclimatology is a subfield of dendrochronology and uses the annual ring-width growth of trees to quantify the effects of a selected climate variable on ring-width growth through statistical methods (Speer, 2010). This study will use tree-ring growth as a measure of tree health and response to monthly climate variables, specifically monthly precipitation and temperature data. While not the focus of this study, tree growth can be limited or enhanced non-climate factors, including insect outbreaks, floods, heat, and fire (Speer, 2010). Both dendrochronological and dendroclimatological techniques were used in this study.

1.4 Urban Heat Island

While the (UHI) was first described in 1833 (Howard, 1833), research into the effects of the UHI on urban tree and environmental impacts is a relatively new field (Yang et al., 2016). The UHI is caused by higher concentrations of surfaces in urban centers such as paved streets absorbing solar energy instead of re-radiating it back into the atmosphere, causing cities to be warmer than surrounding rural areas (Gülten et al., 2016). The larger a city, the greater the effect of the UHI (Oke, 1973). The effects of the UHI on trees is of particular interest, as while trees are noted to have a moderating effect on the UHI, it could simultaneously hamper tree growth (Schneider et al., 2022). In addition, the moderating effects of trees on the UHI is substantive, as shade trees reduction in cities' daytime temperatures can be as much as 7 °C (Soledad Duval et al., 2020).

The UHI can also be a window into possible future climactic conditions in cities. As eastern North America continues to warm, studying the effects of the UHI on tree growth could provide insights into how those species may react to similar climate changes in surrounding rural areas in the years to come (Frank & Backe, 2023). This research could provide key insights on how to best manage and steward species that are at risk from climate change and warming temperatures (Frank & Backe, 2023).

1.5 Eastern North American Forests

1.5.1 Current Growth Patterns in Eastern North American Forests

Southern Ontario is located within the eastern temperate forest range of North America and is at the border between the northern boreal forests of northern Canada and the more southerly deciduous forests that dominate much of the eastern United States. Thus, many of the trees common in the region are growing at the more northerly or southerly limit of their natural

ranges (Goldblum & Rigg, 2005). The forests of the region are characterized by broadleaf deciduous trees such as maples (*Acer*), oaks (*Quercus*), and hickories (*Carya*), as well as some needle-leaved coniferous species such as pines (*Pinus*) (US EPA, 2015). Some of the species growing at the southernmost or northernmost extents of their range respectively include black spruce (*Picea mariana*), a more northerly species, and shagbark hickory (*Carya ovata*), a more southerly species (Koch, n.d.). Trees growing at the southern extents of their ranges may become more stressed by climate-change induced temperature increases, while trees at the northern extents of their ranges may benefit from temperature increases (Sonti et al., 2019; St. George & Ault, 2014; Van Mantgem & Stephenson, 2007). Within the deciduous forests that dominate in southern Ontario the most prevalent growth limiting factors are monthly temperature, particularly winter dormancy, and monthly precipitation (Nuttle et al., 2013).

1.5.2 Projected Growth Patterns in Eastern North American Forests

Warming temperatures in these forests are predicted to have a net positive impact on tree growth rates in the short term, as one of the main limiting factors in eastern deciduous forest growth is winter low temperatures and winter dormancy (Leites et al., 2019). As winters shorten and summers lengthen, trees' growing seasons will increase, with an increase in annual tree-ring growth rates (Goldblum & Rigg, 2005). Increased atmospheric CO₂ levels could also result in short-term elevated tree growth rates, an effect that has already been observed in some urban environments (Chen et al., 2011; Dahlhausen et al., 2018; De Roo et al., 2020)

However, as temperatures continue to increase, trees will likely experience increased temperature, moisture, and biotic stressors. Increased temperatures can cause decreased growth rates in trees by increasing evapotranspiration rates, becoming more pronounced during increasingly common heat waves (Teskey et al., 2015). Periods of elevated temperature are also

associated with increased drought stress due to elevated levels of soil moisture evaporation, further stressing trees (Leites et al., 2019; Teskey et al., 2015). Current predictions show that with the current level of warming most, if not all, current species in eastern forests will see their ideal range migrate northward (Goldblum & Rigg, 2005). Given the rapid rate of warming and associated northward migration of ideal ranges, most tree species are not predicted to be able to keep pace with the movement of their range through natural dispersal mechanisms, possibly leading to large-scale mortality events for many current eastern forest species (Goldblum & Rigg, 2005). Some species with large ranges, such as red oak (*Quercus rubra*) and sugar maple (*Acer saccharum*) are predicted to retain healthy natural stock, as the species will have more time to migrate due to its larger range (Iverson et al., 2019, 2022). However, some species such as black ash (*Fraxinus nigra*) and eastern hemlock (*Tsuga canadensis*) are predicted to face increasing threats from climate change, in part due to their more limited range as well as from other threats, such as insect infestation (Iverson et al., 2019, 2022).

Eastern North American deciduous forests are experiencing an increase in insect infestations and other tree diseases associated with the warming climate (Gandhi & Herms, 2010). Many of these pests are invasive and are proliferating due to a lack of predation or other natural controls that may have been present in their home range (Liebhold et al., 1995). Such invasive pests include the emerald ash borer, a beetle native to Asia, which has decimated North American ash species (*Fraxinus*), which had previously been common not only in natural areas but was commonly planted in cities (Poland & McCullough, 2006). As temperatures continue to warm, the range of several of these insect pests will expand, such as the mountain pine bark beetle (*Dendroctonus ponderosae*) in British Columbia, Canada infesting new areas due to climate change associated warming (Howe et al., 2021). These pests, combined with the

changing climate, pose a major threat to the biodiversity and health of eastern North American forests, which could have consequences for human health and livelihoods that rely on the ecosystem services that forests provide (Howe et al., 2021). Forests have already been shown to suffer from species loss, exhibited by the near total loss of American chestnut (*Castanea dentata*) and the widespread mortality of elm species (*Ulmus*) (Barnes & Delborne, 2019; Potter et al., 2011), giving urgency to better understand potential future biodiversity loss and threats.

1.6 Sampled Species

1.6.1 Red Oak

Red oak (*Quercus rubra*) is a widely dispersed broadleaf deciduous species native to North America, with a range extending from northern Alabama in the United States to Nova Scotia and the Maritime Provinces of Canada (Matthews et al., 2011; Peters et al., 2020; Sander, 1990). The species experiences average temperatures of 4 °C in its northern range and 16 °C in the southern extent of its range, with average precipitation ranging from 760 mm to 2030 mm (Sander, 1990). The species is classified as having intermediate shade tolerance, and grows best in well-drained soils (Sander, 1990).

The species faces serious threats from oak-wilt (*Bretziella fagacearum*) an invasive fungus that has devastated oak species across much of the United States and that has migrated into Canada (Gauthier et al., 2024). While all oak (*Quercus*) species are susceptible to the disease, red oak has been found to be more susceptible than other oaks, such as white oak (*Quercus alba*) (Koch et al., 2010). Urban studies of red oak have been more limited but have found the species to be tolerant to drought and warm summer temperatures, with strong growth in urban environments (Gillner et al., 2013, 2014).

1.6.2 Norway Maple

Norway maple (*Acer platanoides*) is a commonly planted street and park tree native to Europe and widely dispersed across the European continent (Munger, 2003). In North America, the species has been commonly planted as an ornamental tree in urban spaces for its supposed drought and pollution tolerance (Munger, 2003). In its native range in Europe, the species tolerates a wide variety of climates, but seedlings do not tolerate extreme high or low temperatures well (Munger, 2003).

Norway maple, as an invasive species in much of North America's eastern deciduous woodlands, itself poses a danger to native species through outcompeting native species and detrimentally altering native ecosystems (Wyckoff & Webb, 1996). In its native range, the species has demonstrated tolerance to climate-change induced drought (Zimmermann et al., 2015), which has made the species attractive to urban forestry planners in European countries (Lazic et al., 2022).

1.6.3 Sugar Maple

Sugar maple (*Acer saccharum*) is a deciduous hardwood broadleaf species widely distributed across eastern North America, with the species southern range extending to the southern Appalachian Mountains in the American states of Tennessee and North Carolina and its northern range reaching into the Maritime provinces of Canada and southern Quebec (Goodman et al., 1990). The species experiences average temperatures in winter of -18 °C and 16 °C in summer in the northern extent of its range, and winter temperatures of 10 °C and 27 °C in the summer in the southern extent (Goodman et al., 1990).

Sugar maple faces increased stressors from climate change across much of its range, with declines in growth noted in a study from the Adirondack Mountains of New York, possibly

attributed to increased stress from insect infestations and damage from rapid changes in temperature (Bishop et al., 2015). A study in the American Midwest found declines in species growth to be more pronounced at the western end of its range, with high sensitivity to higher summer temperatures (Rudolph & LeBlanc, 2020). The species also faces competition from invasive tree species, including Norway maple (Kloeppel & Abrams, 1995).

1.6.4 Linden

The two sampled linden, or lime, species, European linden (*Tilia x europaea*) and little-leaf linden (*Tilia cordata*) are both natives of Europe yet are commonly planted in North American cities (Eaton et al., 2016; Lande et al., 2019). European linden (*Tilia x europaea*) is a hybrid of little-leaf linden (*Tilia cordata*) and large-leaved linden (*Tilia platyphyllos*) (Jurksiene et al., 2023). Their native range in Europe largely overlaps, with their southern range extending into northern Spain and central Italy and their northern range extending into England, southern Sweden and Norway, and parts of Russia (Eaton et al., 2016). Both species live primarily in areas with wet winters and warmer, dry summers, and are rather drought tolerant (Eaton et al., 2016). Both are commonly planted as a street tree both in their native European range as well as in other similar climates around the world for their longevity and tolerance to drought and adaptation to both hot and cold conditions (Eaton et al., 2016).

Despite being non-native to North America, the species does not commonly propagate into natural areas (Jurksiene et al., 2023; Lande et al., 2019). The species does however have a connection with bumblebee mortality (Fossen et al., 2019; Lande et al., 2019). While research is limited, several studies have suggested that bee mortality may be because of low nutrient density in *Tilia* flowering buds, and that already weakened bumblebees are found deceased near the trees

not directly because of the *Tilia*, but because the bees were unable to gain proper nutrition from the tree flowers (Fossen et al., 2019; Lande et al., 2019)

1.6.5 Austrian Pine

Austrian pine (*Pinus nigra*) is an evergreen conifer native to Europe that has been commonly planted in North America as an ornamental tree and has spread to natural areas (Sullivan, 1993). In its native range it grows mainly in montane forests and scrubland along the mountainous Mediterranean coasts of southern Europe and Turkey, and in North America it is found mainly in the Great Lakes region and New England in temperate climates (Sullivan, 1993). The species is rather drought tolerant and has also been found to be resistant to urban pollutants such as road salt (Sullivan, 1993; Wang et al., 2019).

The species has a limited range in Europe and thus changing climates could limit its range further and prevent the species from migrating to more suitable climates (Martin-Benito et al., 2010). The species has also been observed to have declining growth rates in parts of its natural range in the Carpathian Mountains due to the threats of soil erosion and invasive species (Trajer et al., 2016).

1.7 Literature Review Conclusions

Most of the studies conducted on urban tree responses to urban climate have been conducted in European cities, which can limit the insights to be gained from such studies as climate and species responses can be highly localized, as shown by the varied responses in trees in Szczecin and Berlin (Cedro & Nowak, 2006; Schneider et al., 2022). However, some studies have shown similarities to the results from European cities. One of the few studies conducted outside of Europe in Shenyang, China found similar results to some European studies, with increased urbanity being generally harmful to trees (Chen et al., 2011; Schneider et al., 2022),

but that contrasts to the results from other studies that have found that increased urbanity can enhance growth (Dahlhausen et al., 2018; Pretzsch et al., 2017). Previous research indicates that while there is a demonstrable impact of urban climate on tree growth, the effect can be highly localized and vary between species (Cedro & Nowak, 2006; Pretzsch et al., 2017; Schneider et al., 2022). These differences have also been found to differ within the city itself, with growth patterns and tree physiology being different between street and park trees of the same species within the same city (Lv et al., 2024; North et al., 2018) These patterns and findings underscore the importance of conducting a study in southern Ontario, not only because of the current lack of knowledge but also because of the importance of southern Ontario within Canada given its large population (Government of Canada, 2022). By sampling and analyzing trees from urban settings within the City of Toronto, this study aims to provide insight into growth trends, climate sensitivities, and general health of tree species growing in a range of urban environments.

1.8 Research Question and Objectives

This study aims to answer the following questions: what is the impact of selected climate variables (temperature and precipitation) on the radial growth rates of 5 commonly planted urban tree species in the city of Toronto, Ontario, and which of those species are and are not well-suited for planting in the urban environment of Toronto given current warming trends? Through this research I aim to be able to provide a more complete picture of the climate-growth dynamics of Toronto's urban forest, to make predictions about the long-term viability of the sampled species in the city, and to make management recommendations to the city based on these results.

Chapter 2 : Methods

2.1 Study Sites

Field work was conducted in May, June, and July of 2023 in the City of Toronto. Toronto is the largest city in Canada, with an estimated population of 3,025,647 in the city proper and an urban metropolitan population of 6,471,850 (City of Toronto, 2023). The city is relatively dense compared to other Canadian cities, with 59% of the city's housing being apartment-style dwellings (Statistics Canada, 2019), and a large metropolitan urban sprawl, with the metropolitan area covering 5,905.84 km² and a metropolitan population density of 1050.7 people per square kilometer (Statistics Canada, 2021). Toronto is situated on the north shore of Lake Ontario and experiences mild to warm summers with average summer temperatures of 22 °C, and cool to cold snowy winters with average winter temperatures of 0 °C (Figure 2.1) (Environment & Climate Change Canada, 2023).

The city is located at the northern limit of North American Eastern Carolinian forests. Common native species of trees in the Toronto area include eastern white pine (*Pinus strobus*), sugar maple (*Acer saccharum*), sycamore (*Platanus occidentalis*), poplar (*Populus spp.*), and red oak (*Quercus rubra*) (Government of Ontario, 2021).

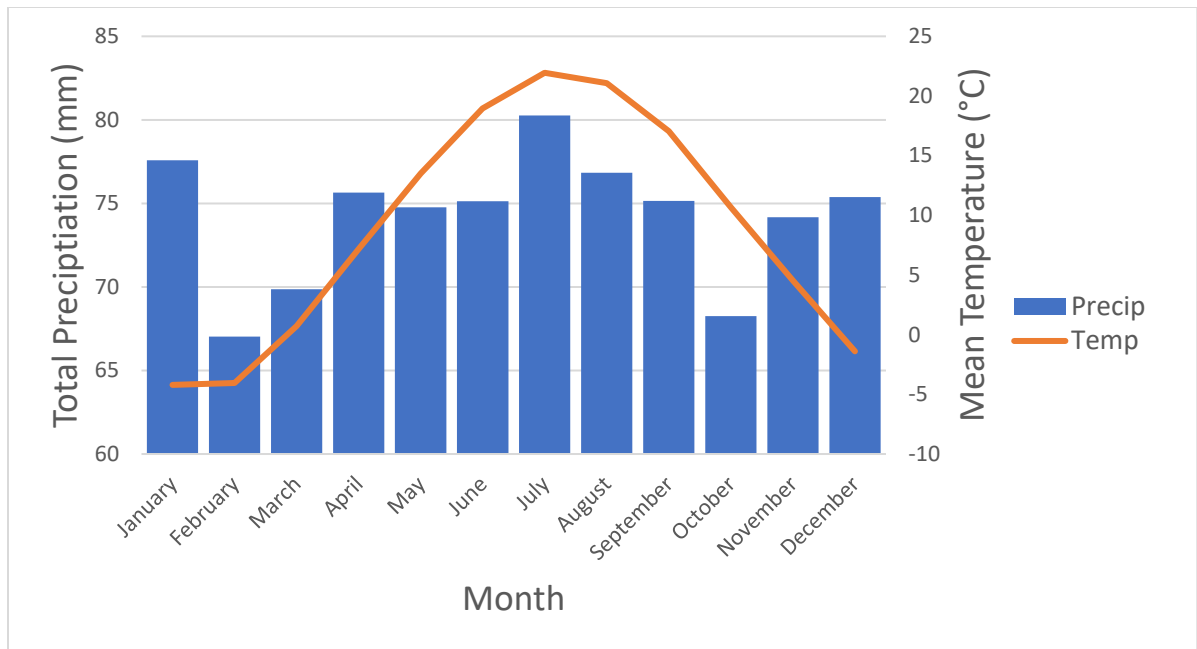


Figure 2.1: Climograph for the city of Toronto with data from 1900-2023

(Source: Environment Canada, 2023).

The City of Toronto has jurisdiction over approximately 1500 parks, parkettes, playgrounds, and other green spaces. The largest park in the city is High Park, which is over 140 hectares and includes remnants of black oak savannah, a threatened ecosystem which formerly spanned much of the southern Ontario region (City of Toronto, 2018). Approximately 28.4% of the city is considered to have an urban tree canopy, with the city counting a total urban tree count of approximately 11.5 million trees, with 614,227 of those being city-maintained street trees (City of Toronto, 2018). According to the City of Toronto (2018), the four most common street trees in the city are non-native Norway maple (*Acer platanoides*), native honey locust (*Gleditsia triacanthos*), non-native blue spruce (*Picea pungens*), and non-native littleleaf linden (*Tilia cordata*) (Figure 2.2).

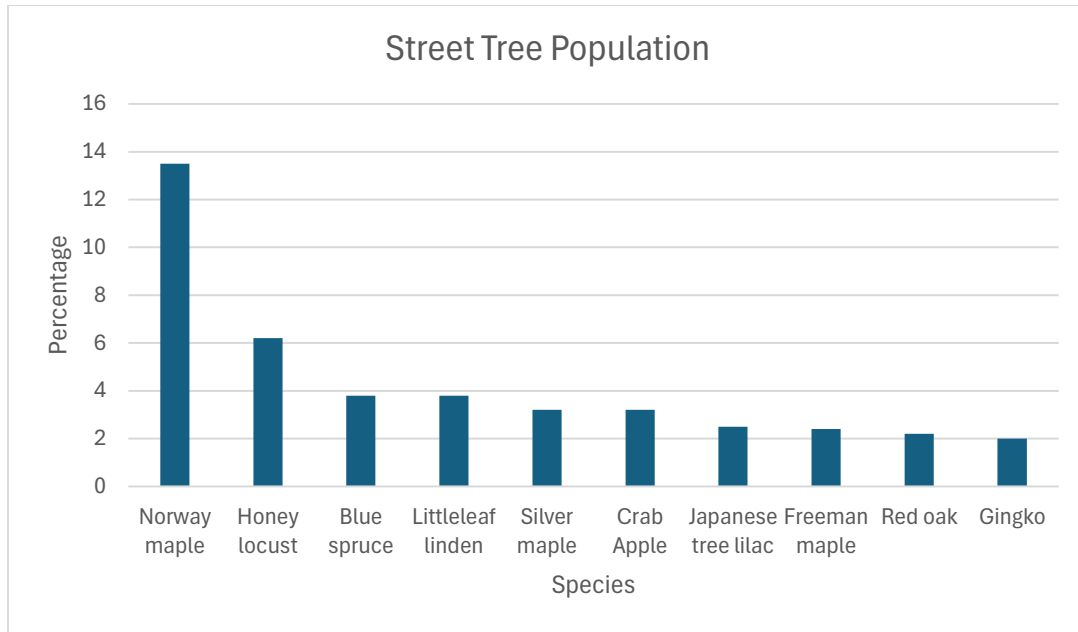


Figure 2.2: The ten most abundant species of street trees in Toronto as a percentage of total street tree population.

(Source: City of Toronto, 2018)

Sampled species included the native *Quercus rubra* (red oak) and *Acer saccharum* (sugar maple), and the non-natives *Acer platanoides* (Norway maple), *Tilia x europaea* (European linden), *Tilia cordata* (little-leaf linden), and *Pinus nigra* (Austrian pine). These species were chosen for their prevalence in the city in both Street and Park locations and because most individuals of each species were of a suitable size (see below) for sampling. The mix of native and non-native species allows for comparisons of the growth trends of non-native versus native species. Some common native species, such as honey locust (*Gleditsia triacanthos*), were not sampled as they were not common in accessible city-owned locations and rarely exceeded the minimum size threshold required by the City of Toronto research permit. All trees sampled were >20 cm dbh (diameter at breast height) to assure adequate ring counts for analyses and < 80 cm dbh per the research permit conditions. All sampled trees were free of visual signs of disease or major damage, such as a hollow/damaged trunk or missing branches. For each species, a minimum of 20 trees were cored to ensure a sufficient sample size from both street rights-of-way

and within city parks. All sites were city-owned and managed. “Park” trees were those growing in officially designated and maintained City of Toronto parks. Parks sampled were Chorley Park, Withrow Park, Queens Park, St. James Park, High Park, and Eglinton Park (Table 3.3 and Figure 3.2). These parks were chosen based on the abundance of target species and their location being either within or close to the downtown urban environment. “Street” locations varied, with sample sites chosen based upon trees being <5 m from a roadway, and not in a private residential garden (Table 2.1).

Sample Location	Austrian Pine	Linden	Norway Maple	Red Oak	Sugar Maple	Total Trees
Park	28	25	26	25	25	129
Chorley Park	16	2	2	11	5	36
Eglinton Park		4	9			13
High Park		13			7	20
Queens Park	9	4	10	5	2	30
St. James Park		2	5	9		16
Withrow Park	3				11	14
Street	25	25	25	20	20	115
Jacks Ave				5		5
Mutual St			8			8
Chartland Blvd					7	7
Hillmount Ave				5		5
Bill Bolton Arena			6		1	7
Brentcliffe Road	7					7
Carstowe Road		5				5
Clinton Street Junior Public School	12	2	4			18
Devonshire Place		3	1			4
Dewson Street Public School		2				2
Harbord Collegiate Institute		1				1
Newgate Parkette	6					6
Newtonbrook Creek		8				8
Nob Lane					8	8
Northern Secondary School		3	1			4
Riverdale Collegiate Institute					2	2
Rose Lawn Cemetery			1			1
St. George Street				3	2	5
Whitney Park Street Trees		1		7		8
Withrow Ave Junior Public School			4			4
Grand Total	53	50	51	45	45	244

Table 2.1: Sampled locations and number of each species collected from listed location.

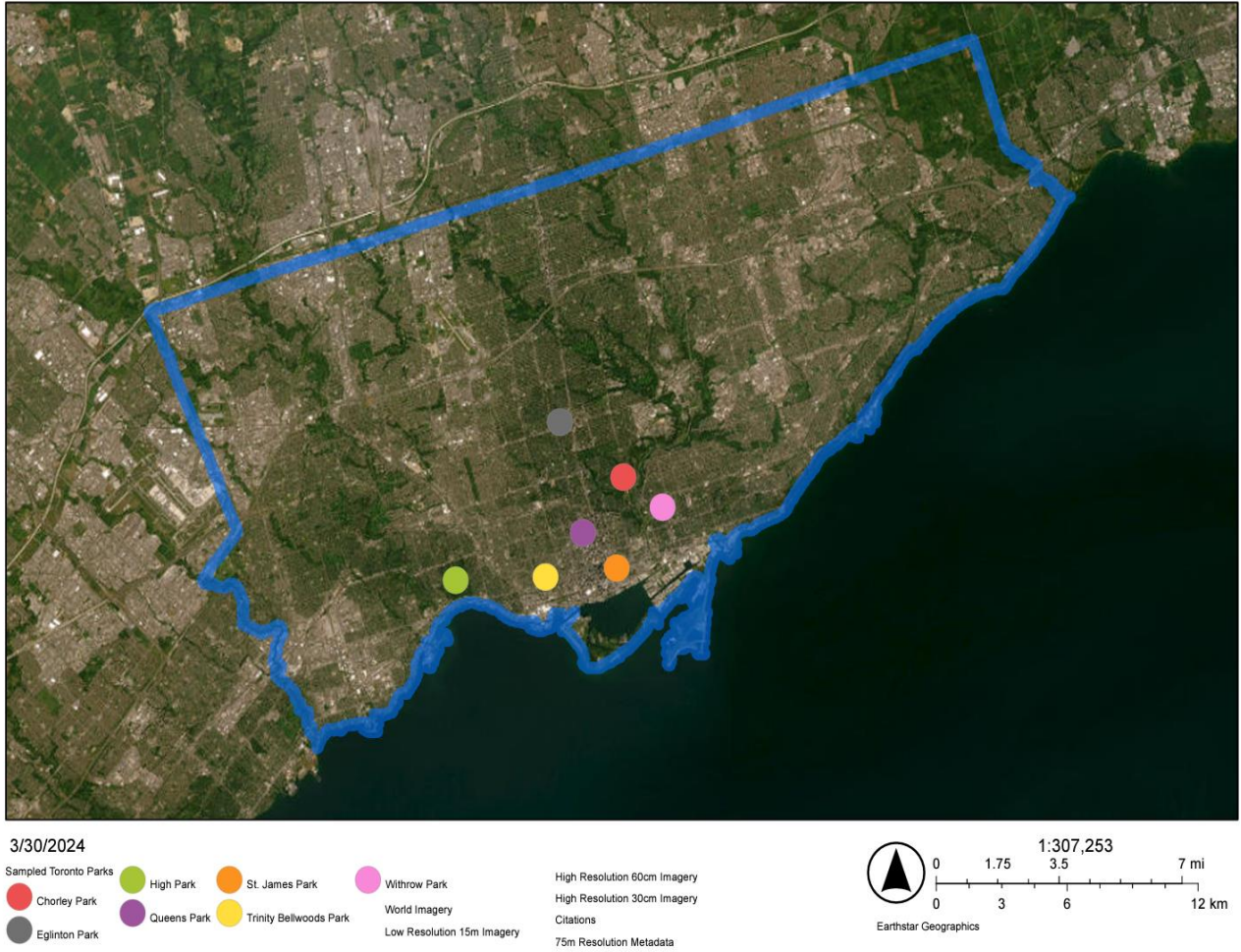


Figure 2.3: Sampled Toronto parks. 5 parks in total were sampled.
 Blue line is Toronto city limits.

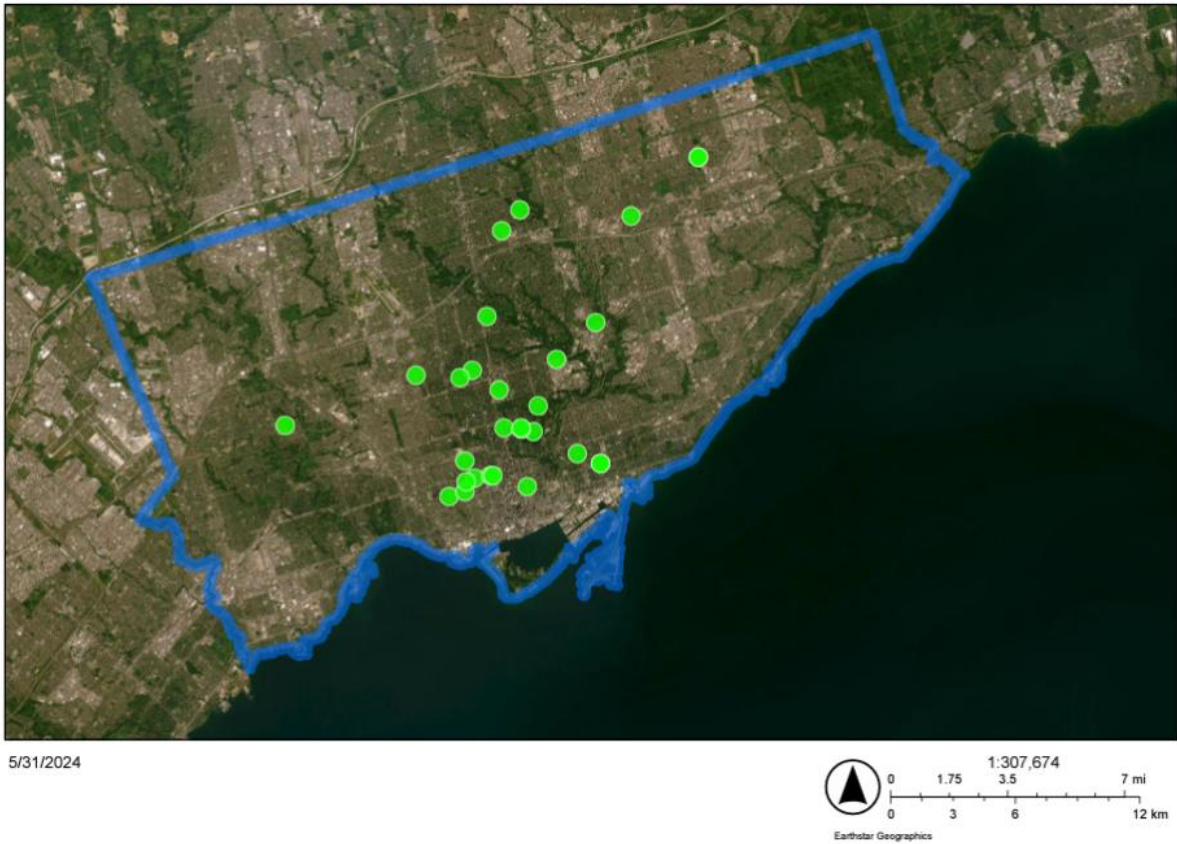


Figure 2.4: Sampled Toronto Street Trees Locations. 20 street locations were sampled in total.

Blue line is Toronto city limits.

2.1.1 Sampled Parks

Chorley Park is a 5 ha park located in the Rosedale neighborhood, surrounded by mostly low-rise single-family homes and forested areas in the Don River Valley (City of Toronto, 2018) (Figure 2.3). The park consists mostly of deciduous hardwood species and has a mature canopy. Individuals of all sampled species were collected at Chorley Park (Table 2.1).

Withrow Park is an 8 ha park in the North Riverdale neighborhood (City of Toronto, nd.) and is surrounded by low- to medium-rise single family homes and multiplexes, approximately 400 m from Danforth Avenue. The park has several large open fields and ball diamonds, with

most species being deciduous hardwoods. Sugar maple and Austrian pine were sampled in this park (Table 2.1).

Queen's Park is a 67 ha park in the downtown area surrounded by high-density high-rise buildings to the south, and the campus of the University of Toronto to the north. The park is adjacent to the grounds of the Ontario Legislative Assembly building and receives a considerable amount of foot traffic (City of Toronto, nd.). The park has a mature canopy and consists predominantly of hardwood deciduous species, with several exotic planted species. Individuals of all sampled species were collected at Queen's Park (Table 2.1).

St. James Park is a 1.5 ha park located next to the Anglican Cathedral of St. James in the Old Town section of downtown. The park has the layout of formal gardens and has planted flowerbeds and walkways throughout the park (City of Toronto). The park is surrounded by high-density development with mixed-use high-rise buildings in the area. The park consists mostly of deciduous hardwood species. Red oak, linden, and Norway maple were collected at St. James' Park (Table 2.1).

High Park is a 161 ha park in the eponymously named High Park neighborhood. Approximately two-thirds of the park is kept in a natural state with little to no planting or tree pruning (City of Toronto, nd.). The tree cover is dominated by hardwood deciduous species. The park is surrounded to the east and west by residential neighborhoods of medium-low density housing, to the north by high-density development, and to the south by the Gardiner Expressway and Lake Ontario. Linden and sugar maple were collected at High Park (Table 2.1).

Eglinton Park is a 9 ha park in the Midtown neighborhood which has mostly recreational facilities and sports fields (City of Toronto, nd.), with some forested areas in the southwest

corner of the park. The park has high-density mixed-use development to the east, medium density mixed-use development to the south and southwest, and low-density residential neighborhoods to the west and north. The park's species are mostly deciduous hardwood, with several maple species. Norway maple and linden were collected in the park (Table 2.1).

2.1.2 Sampled Streets

Jackes Avenue is a small side street off Yonge Street in the Yonge-St. Clair neighborhood. The street was planted with hardwood and conifer trees, including red oak and Austrian pine with high rise buildings surrounding the street, and the David A. Balfour Park to the east of the street. Red oak was collected on this street (Table 2.1). Austrian pine was not collected at this location as it was abundant in other sample locations.

Mutual Street is a street in downtown with high density development. The street's planted trees mostly consist of Norway maple and Ginko (*Ginkgo biloba*). Norway maple were collected from a patch of planted trees adjacent to a high-rise building (Table 2.1).

Chartland Boulevard is a street that runs through a residential neighborhood of Scarborough. The area is predominantly low-density single-family homes with most street trees being sugar maple and Norway maple. Sugar maple were collected from a stand of trees adjacent to the road (Table 2.1). Norway maple was not sampled at this site, being abundant in other street locations.

Hillmount Ave is a street in a residential area of North York. The surrounding area is predominantly low-density single-family homes with some commercial space to the east and west of the street. Red oak were located along the street in city-owned verge adjacent to the road (Table 2.1).

2.2 Field Sampling Methods

Park tree cores were collected from trees that were >10 m from roadways adjacent to the park (most were 25+ m from roadways), while street trees were collected from trees on verges < 5 m from roads. Sampled tree species were dispersed across the city so as to collect samples from a variety of growing locations. Cores were collected from trees that were 20-80 cm dbh. Cores were extracted using a 5.15 mm diameter Haglof increment borer at approximately 1.3 meters height. Two cores were extracted from each tree to build in redundancy in sampling, and to assure that at least one of the samples was free of irregularities (internal branch scars, rot, etc.). Each cored tree's location was recorded using a Garmin inReach Explorer+ handheld GPS. Once collected, cores were placed in uniquely numbered plastic straws for transport and safe storage for processing at the lab. Each core's ID number, species, tree dbh, and geographic coordinates were recorded in a database.

2.3 Laboratory Methods

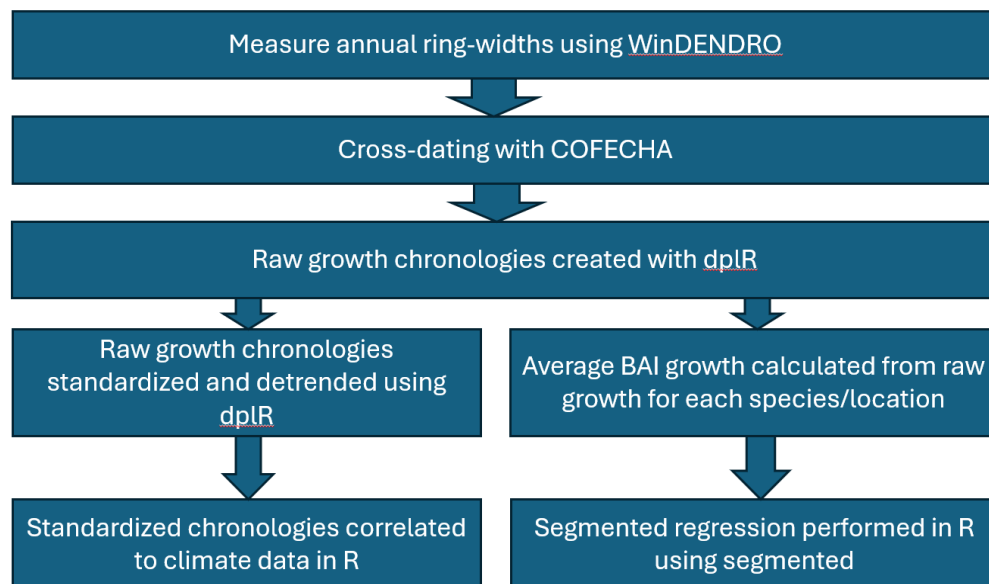


Figure 2.5: Flowchart of laboratory and analytical methods.

All tree cores were air-dried for >24 hours and transported to the Biogeography Lab at Western University for analysis using standard dendroclimatological techniques (Goldblum & Rigg, 2005; Speer, 2010). The cores were glued to wooden mounts and then sanded to enhance ring visibility for analysis. The cores were sanded with progressively finer sandpaper, starting with 80 grit sandpaper on a 4x36" Ryobi belt sander, gradually progressing to finer grit (220), with the final stage manual sanding with 600 grit. The cores were then scanned with an EPSON Perfection V800 Photo scanner, modified by Regent Instruments (regent.qc.ca) for tree ring detection and processing. A 10-40x magnification stereo microscope was used to assist in the detection and counting of faint rings. For each core, ring widths were measured to the nearest 0.01 mm with WINDendro (regentinstruments.com/assets/windendro_about.html) software. Rings were tentatively assigned calendar years from the last complete ring (2022) to the earliest complete ring on the core.

2.4 Analytical Methods

2.4.1 Cross-Dating

Cross-dating (correctly assigning calendar years to each ring) is an essential step in tree-ring analysis to ensure there are minimal errors in the measuring process as samples gathered from the same species in proximity should have comparable growth patterns (Speer, 2010). Ring width series from each species/location groupings were analyzed with COFECHA (Holmes, 1983), dendroclimatological software that performs cross-dating of tree-ring series. COFECHA evaluates the correlation between each core sample and the "master chronology" consisting of all samples (Speer, 2010). Cross-dating can identify possible missing or false rings within a series by comparing a sample with others in the dataset to ensure that the measured cores have been counted and measured correctly (Speer, 2010). A master chronology of all samples for each

species from each location (Park and Street separately) was developed in COFECHA and short segments of each core were compared to the master chronology to identify possible dating errors. A segment length of 20 years lagged by 10 years was chosen for the purposes of this study due to the younger age of the sampled urban trees. Cross-dating yielded intercorrelations metrics for each core, with cores exhibiting a mean intercorrelation of less than 0.3 excluded from the final analysis in order to ensure proper dating and matching of cores and to keep in line with standard dendroclimatological practices (Bartens et al., 2012, Speer, 2010). For the 10 species/location combinations (i.e. street red oak, park sugar maple), COFECHA produced a single cross-dated master chronology from the sampled trees.

2.4.2 Detrending

Detrending is a necessary component of tree-ring analysis to remove biologic growth trends unrelated to climate, in keeping with other dendroclimatological studies (Cedro & Nowak, 2006, Dahlhausen et al., 2018, Goldblum and Rigg 2005). The 10 cross-dated chronologies were detrended using the dplR tree ring dating package (Speer, 2010) in R Studio. This created 10 chronologies for analysis, one for each species grouped by location. A cubic smoothing spline was used to standardize and detrend the series because of its ability to smooth noisy data such as tree-ring growth. The spline was fitted using a frequency response of 0.5 and a wavelength of 0.67, in keeping with standard practice (Cook & Kairiukstis, 1990; Fritts, 2001). In total, there were 179 growth series used for analysis (Table 2.2). These processes are visualized in Figure 2.5, with raw R outputs for standardization and sample depth shown in Appendix Figures 1, 4, 7, 10, 13, 16, 19, 22, 25, & 28.

Site	Species	Number of Trees	Year Range	Average Series Length	Average DBH (cm)	Intercorrelation	Mean Sensitivity
Park	Linden	12	1969-2022	39	58.164	0.416	0.373
Street	Linden	17	1964-2022	40	50.984	0.453	0.346
Park	Norway Maple	19	1940-2022	44	56.576	0.519	0.385
Street	Norway Maple	20	1972-2022	42	40.180	0.568	0.407
Park	Red Oak	23	1912-2022	42	52.932	0.550	0.242
Street	Red Oak	18	1865-2022	65	56.405	0.540	0.224
Park	Austrian Pine	18	1968-2022	40	51.746	0.440	0.278
Street	Austrian Pine	19	1934-2022	43	41.708	0.506	0.247
Park	Sugar Maple	21	1970-2022	44	46.180	0.446	0.411
Street	Sugar Maple	12	1973-2022	39	49.190	0.459	0.395
Total/Average		179		44	50.407	0.490	0.331

Table 2.2: Sampled species by site with associated dendrochronological statistics.

2.4.3 Climate Data

Each of the 10 detrended chronologies were correlated with mean monthly temperature and total monthly precipitation records obtained from the Government of Canada’s homogenized climate data for Toronto (Environment Canada, 2023). Temperature data was available from 1840 to the present, and precipitation data from 1849 to the present. Homogenized monthly Toronto temperature data ended in 2006, with the remaining years obtained from the Toronto City Station and Toronto Pearson International Airport Station (Environment Canada, 2023).

2.4.4 Climate/Growth Correlations and Statistical Limitations

For each of the 10 chronologies, the treeclim package in R was used to determine correlations between annual tree growth and monthly climate variables. Previous months of May, June, July, August, September, October, November, December and current months of January, February, March, April, May, June, July, August, and September were analyzed. This time span accounts for the effects of the current year’s climate on growth as well as potential lag effects from the previous year’s climate (Zang and Biondi, 2015). Two types of correlation analyses were conducted: static and moving. A static correlation analysis evaluates the entire growth period of each chronology to determine the nature of the relationship between each climate variable and tree growth for the *entire* temporal record of growth. By contrast, a

moving analysis of 19 years overlapped by one year, was conducted to evaluate the temporal nature of correlations for each climate variable and tree growth throughout the period of growth. The treeclim package includes a bootstrapping scheme to attempt to avoid over-fitting response functions and to account for temporal autocorrelation (Zang and Biondi, 2015). While bootstrapping attempts do account for these potential errors, the sample size used could still limit the statistical power of the method, as well as the possibility of urban microclimate impacting tree growth on a more localized scale than examined in this study (Dahlhausen et al., 2018; Pretzsch et al., 2017), thus leading to type 1 statistical errors.

2.4.5 Basal Area Index (BAI)

Trends in growth over time and between species/location categories was analyzed using of Basal Area Index (BAI) values (Equiza et al., 2017). BAI quantifies annual additions in wood basal area per year (mm^2/yr). This was accomplished using the raw ring width data of each tree by location and calculating BAI in R using the BAI.in package (Bunn et al., 2023). The analysis converted the collected ring-width (mm) series to ring-area (mm^2/yr) series, based on the measured diameter of the tree. The calculation was performed from the bark in as the pith of the tree was not always reached in all samples.

Each analysis produced a BAI increment for each year of each sampled tree. These growth rates were averaged for each species by sample location (i.e. 'Park Linden'). The average increment of yearly BAI increase was then plotted to visualize average growth per year for each sampled species.

2.4.6 BAI Segmented Breakpoint Regressions

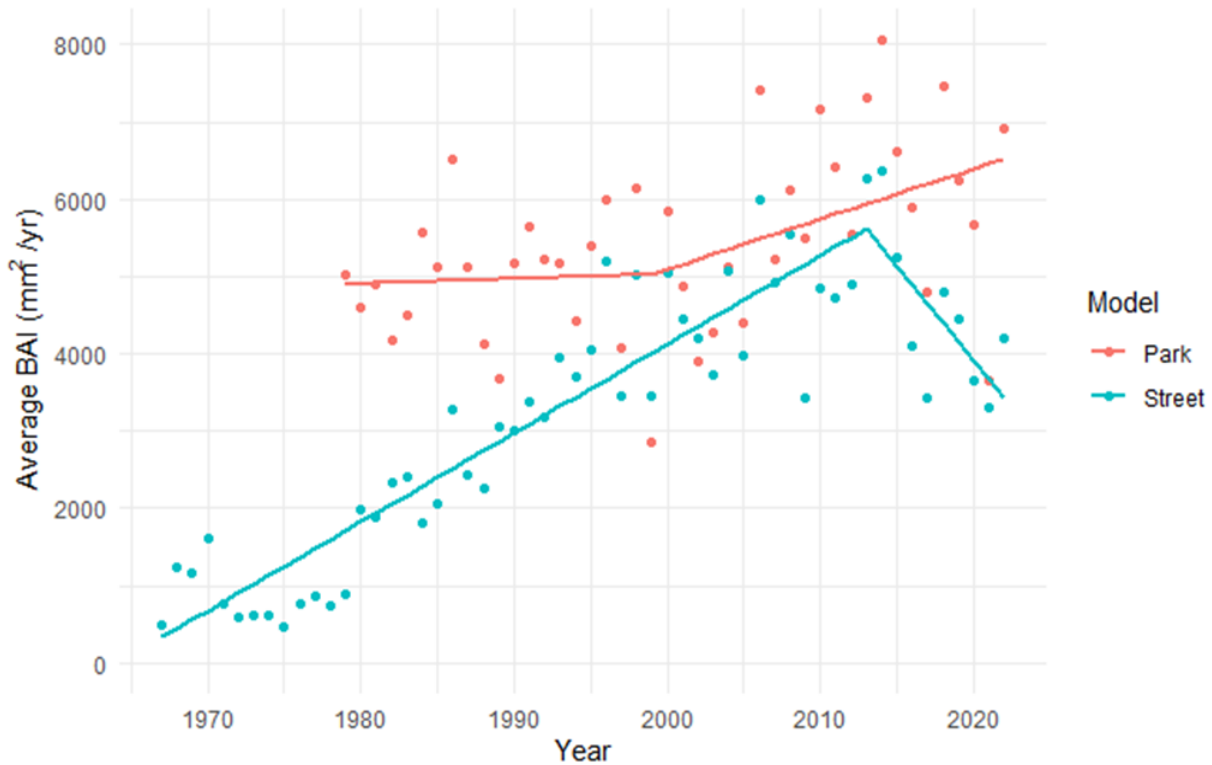


Figure 2.6: An example of segmented linear regression model.

Note the two distinct linear models for each species growing location.

To identify statistically significant increases or decreases in growth trends over time a segmented linear regression was fit to each species' average BAI growth time series. This was performed with the 'segmented' package in R (Fasola S & Kuchenhoff, 2018). Each species' average BAI time series was first fit with a single linear regression equation, followed by a Davies' test for significance to determine whether a breakpoint was warranted to improve the regression model resulting from a change in slope during the time series (Muggeo, 2003, 2008). If warranted, then the 'segmented' package was used to fit a second linear model to the data (for the segment before and the segment after the breakpoint), and if needed a third or fourth model to best fit significant temporal trend shifts. Model fitness (i.e., no breakpoint, one breakpoint, two breakpoints, etc.) was evaluated using the lowest number from both Akaike Information

Criterion (AIC) and Bayesian Information Criterion (BIC) (Cook & Pederson, 2011; Sakamoto & Ishiguro, 1986) values to determine the number of breakpoints best suited to fit the time series. In order to maintain simplicity, if there was a discrepancy between AIC and BIC values, or there was less than a 0.10 difference in values, the smaller number of breakpoints would be used for the final model (Muggeo, 2003, 2008). Segmented regressions for each species and location was plotted to visualize trends (Figure 2.6).

Chapter 3 : Results

3.1 Introduction

As a result of cross-dating analyses, several cores were excluded from the final chronologies due to low individual intercorrelation values (detailed in Methods). Excluded cores were: 10 park Austrian pine, 6 street Austrian pine, 13 park linden, 8 street linden, 7 park Norway maple, 5 street Norway maple, 2 park red oak, 2 street red oak, 4 park sugar maple, and 8 street sugar maple. Thus, the sample sizes for all growth and climate correlation analyses were: 18 park Austrian pine, 19 street Austrian pine, 12 park linden, 17 street linden, 19 park Norway maple, 20 street Norway maple, 23 park red oak, 18 street red oak, 21 park sugar maple, and 12 street sugar maple. Intercorrelation values, which is a measure of similarity between samples, for the ten chronologies ranged from 0.416 to 0.568 and mean sensitivity, which is the average sensitivity of tree ring growth to climate, for all chronologies averaged 0.331 (Table 3.1).

Site	Species	Number of Trees	Year Range	Average Series Length	Average DBH (cm)	Intercorrelation	Mean Sensitivity
Park	Linden	12	1969-2022	39	58.164	0.416	0.373
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Street	Sugar Maple	12	1973-2022	39	49.190	0.459	0.395
Total/Average		179		44	50.407	0.490	0.331

Table 3.1: Metrics for each chronology used in the study.

3.2 Static and Moving Dendroclimatological Analyses

3.2.1 Static Precipitation Analysis

A static climate analysis identifies statistically significant relationships between the selected climate variable(s) and analyzed for *all years* of radial growth data. In this study, the analysis period covered 17 months of climate data: mean monthly temperature and total monthly precipitation for May-December of the previous year and January-October for the current year. The analysis (detailed in Methods) identifies statistically significant ($p < 0.05$) correlations between monthly climate variables and radial growth.

3.2.1.1 Linden Response to Precipitation

The radial growth of both park and street lindens were not correlated with precipitation over the full period of growth (Table 3.2).

3.2.1.2 Norway Maple Response to Precipitation

There was a significant ($p < 0.05$) positive correlation between radial growth of park Norway maple and previous October and November precipitation (Table 4). Radial growth of street Norway maple exhibited a significant ($p < 0.05$) positive correlation with June precipitation (Table 3.2).

3.2.1.3 Red Oak Response to Precipitation

Park red oak exhibited a significant ($p < 0.05$) negative correlation between growth and previous June precipitation and positive correlation with current July precipitation (Table 4). Radial growth of street red oak exhibited a significant ($p < 0.05$) positive correlation with current March, June, and July precipitation (Table 3.2), with more months having positive correlations in street locations than park (Table 3.2).

3.2.1.4 Austrian Pine response to Precipitation

The radial growth of park Austrian pine was not statistically correlated to any total monthly precipitation values (previous May to current October) when considering the full period of growth (1968-2022) (Table 4). However, the radial growth of street Austrian Pine exhibited a significant ($p < 0.05$) positive correlation with current September precipitation (Table 3.2).

3.2.1.5 Sugar Maple Response to Precipitation

The radial growth of park sugar maple exhibited a significant ($p < 0.05$) positive correlation with previous August precipitation (Table 4). Radial growth of street sugar maple was significantly ($p < 0.05$) positively correlated with previous June precipitation when considering the full period of growth (1973-2022) (Table 3.2).

Site-Species	Previous								Current									
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Park Linden																		
Street Linden																		
Park Norway Maple						0.29	0.32											
Street Norway Maple														0.41				
Park Red Oak		-0.23													0.34			
Street Red Oak											0.24			0.28	0.26			
Park Austrian Pine																		
Street Austrian Pine																	0.24	
Park Sugar Maple				0.35														
Street Sugar Maple		0.34																

Table 3.2: Static climate correlations for radial tree growth and precipitation from May of the previous year to October of the current year.

Significant ($p < 0.05$) correlations are shaded with blue indicating a positive correlation and red a negative correlation. Raw static precipitation plots for each species in Appendix Figures 2, 5, 8, 11, 14, 17, 20, 23, 26, & 29.

3.2.2 Static Temperature Analyses

3.2.2.1 Linden Response to Temperature.

The radial growth of park linden was not statistically correlated to any total monthly temperature values (previous May to current October) when considering the full period of growth (1969-2022) (Table 3.3). Street Linden exhibited a significant ($p < 0.05$) negative relationship with current June temperature (Table 3.3).

3.2.2.2 Norway Maple Response to Temperature

The radial growth of Norway maple was not statistically correlated to any total monthly temperature values (previous May to current October) when considering the full period of growth (1940-2022) (Table 3.3). Radial growth of street Norway maple exhibited a significant ($p < 0.05$) negative correlation with current summer (July) temperature (Table 3.3).

3.2.2.3 Red Oak Response to Temperature

Park red oak radial growth was not exhibited a significant ($p < 0.05$) negative correlation with current July temperature (Table 3.3). The radial growth of street red oak showed no statistical correlation to any monthly temperature values (previous May to current October) when considering the full period of growth (1865-2022) (Table 3.3).

3.2.2.4 Austrian Pine Response to Temperature

Park Austrian pine exhibited a significant ($p < 0.05$) positive correlation with current January temperature (Table 3.3). The radial growth of street Austrian pine showed no statistical correlation to any monthly temperature values (previous May to current October) when considering the full period of growth (1934-2022) (Table 3.3).

3.2.2.5 Sugar Maple Response to Temperature

Park sugar maple radial growth exhibited a significant ($p < 0.05$) negative relationship with previous June and July and current January temperatures (Table 3.3). Radial growth of street sugar maple exhibited a significant ($p < 0.05$) negative relationship to previous June and July temperature (Table 3.3).

Site-Species	Previous									Current									
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	
Park Linden																			
Street Linden														-0.30					
Park Norway Maple																			
Street Norway Maple															-0.35				
Park Red Oak															-0.24				
Street Red Oak																			
Park Austrian Pine									0.28										
Street Austrian Pine																			
Park Sugar Maple		-0.38	-0.51						-0.32										
Street Sugar Maple		-0.50	-0.46																

Table 3.3: Static climate correlations for radial tree growth and temperature from May of the previous year to October of the current year.

Significant ($p < 0.05$) correlations are shaded with blue indicating a positive correlation and red a negative correlation. Raw static precipitation plots for each species in Appendix Figures 3, 6, 9, 12, 15, 18, 21, 24, 27, & 30.

3.2.3 Moving Precipitation Analysis

A moving climate analysis differs from a static climate analysis in that it evaluates temporal stability of the relationship (correlation) between the selected climate variable and radial growth over the period of overlapping tree-ring and climate records. Provided are the

results from both the precipitation and temperature moving climate-growth correlations with summary tables provided at the end of each section for each of the two variables (Tables 3.4-3.5).

3.2.3.1 Linden Response to Precipitation

Park linden radial growth exhibited a significant ($p < 0.05$) positive relationship with both precipitation for previous August from the late 1980s to the early 2010s and current June precipitation from the early 1990s to the late 2010s (Figure 3.1). Similarly, street linden radial growth shows a significant ($p < 0.05$) positive relationship for current June precipitation nearly continuously from the mid 1980s to 2010, a short period of significant ($p < 0.05$) negative relationship with current February precipitation in the mid 1960s to late 1970s, and a short period of significant ($P < 0.005$) negative correlations with previous July precipitation from the mid 1990s to the mid 2000s (Figure 3.2).

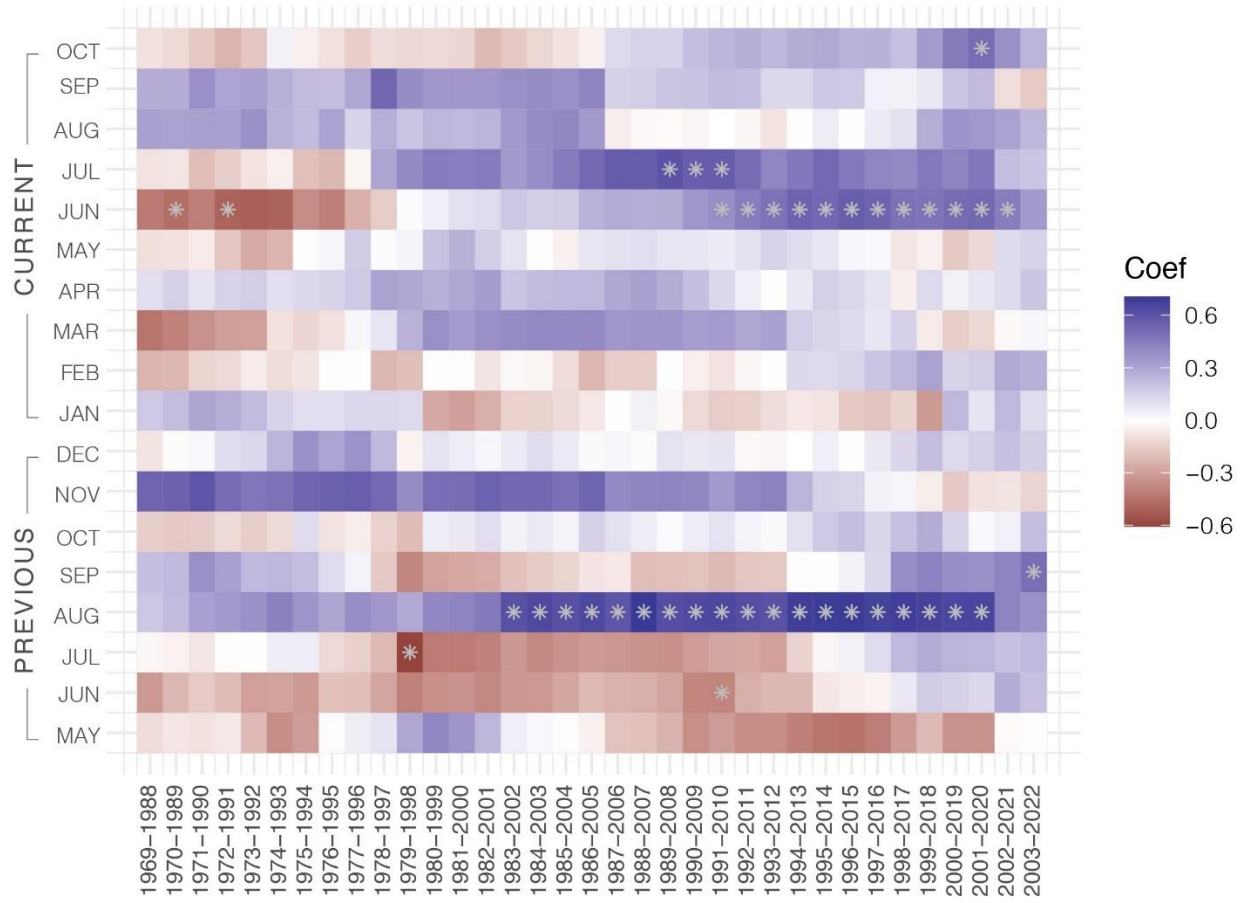


Figure 3.1: Moving climate correlations for park linden radial growth and monthly total precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

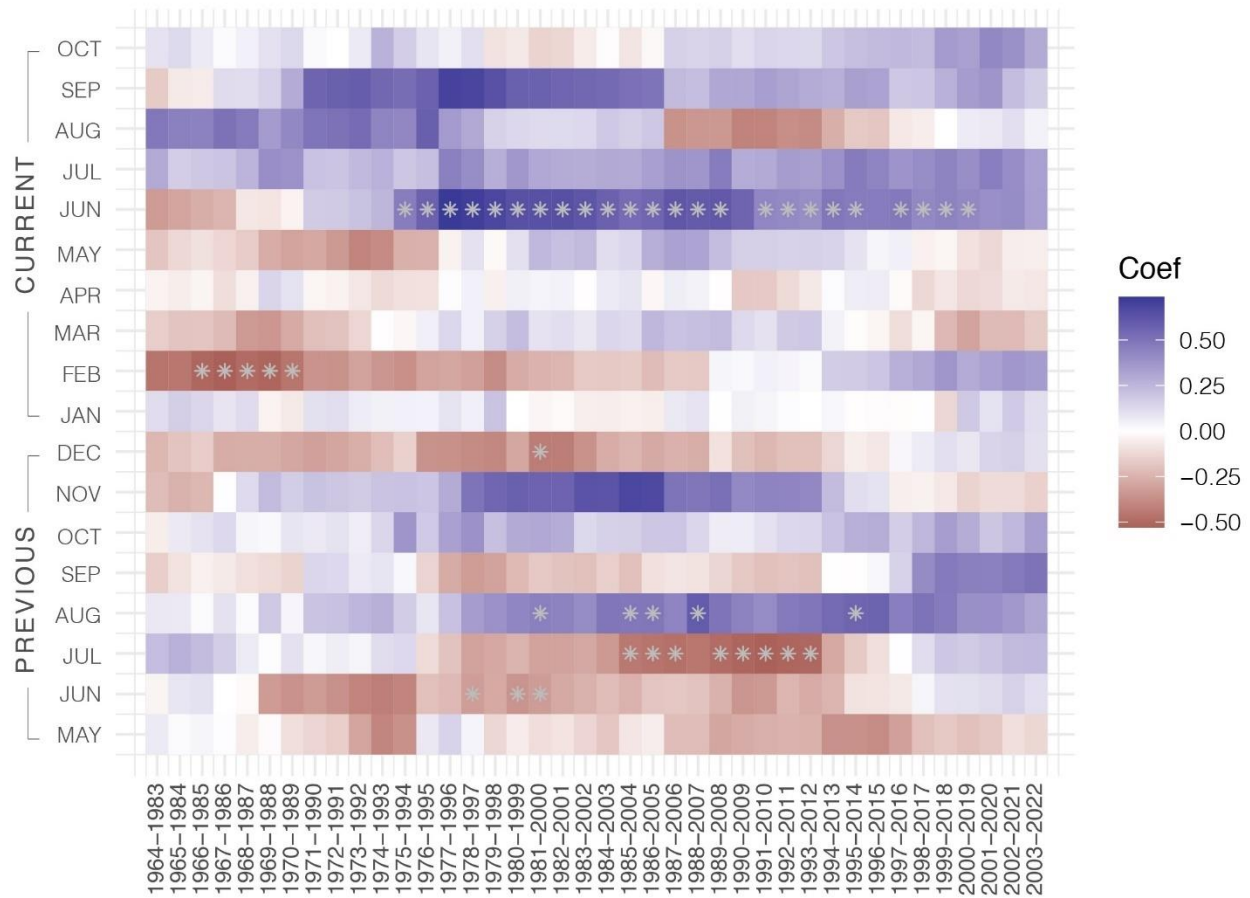


Figure 3.2: Moving climate correlations for street linden radial growth and monthly total precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

3.2.3.2 Norway Maple Response to Precipitation

Park Norway maple showed a significant ($p < 0.05$) negative relationship between radial growth and precipitation in current June and previous May from the beginning of the sampled period (1940) to the early 1960s, but the relationship with current June precipitation has trended significantly positive in recent years starting in the mid-1990s. Previous November, previous October, and previous August precipitation saw periods of a positive relationship with radial growth from the early 1940s to late 1960s for previous October and November and from the

early 1980s to late 2000s for previous August (Figure 3.3). Like park Norway maple, street Norway maple showed a significant ($p < 0.05$) positive relationship between radial growth and current summer (June) precipitation from the late 1980s to the present (Figure 3.4).

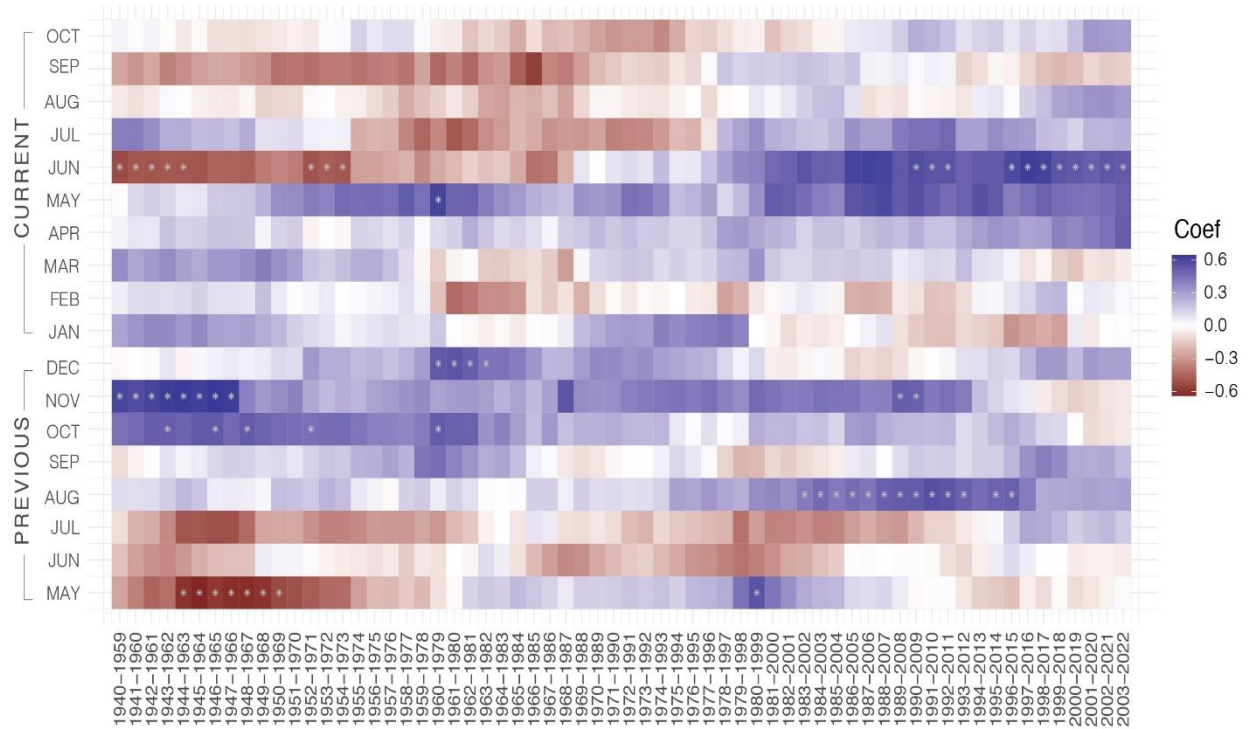


Figure 3.3: Moving climate correlations for park Norway maple radial growth and monthly total precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

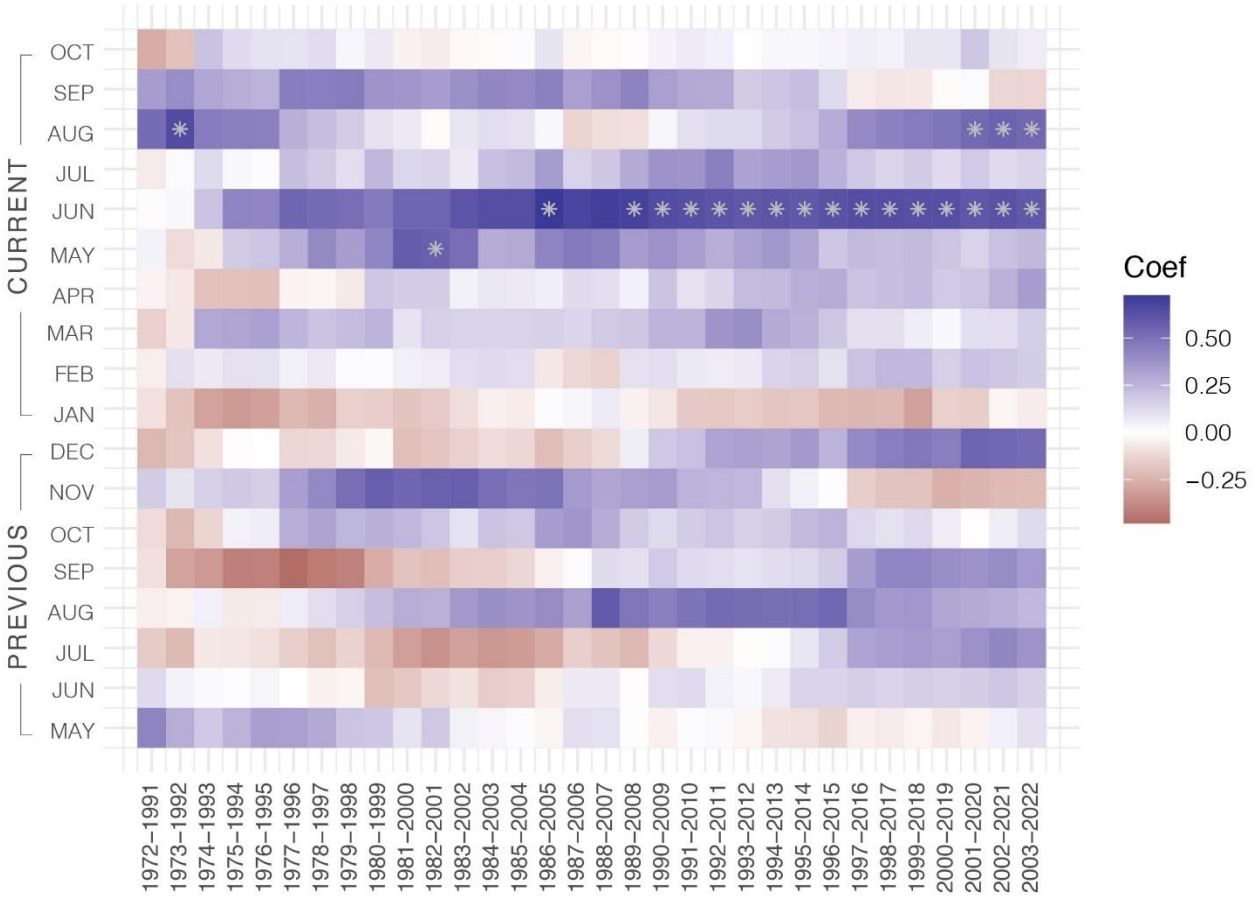


Figure 3.4: Moving climate correlations for street Norway maple radial growth and monthly total precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.3.3 Red Oak Response to Precipitation

Red oak radial growth in parks showed a significant ($p < 0.05$) negative correlation between radial growth and precipitation for a number of short periods: previous June from early 1930s - late 1950s and from the early to mid-1980s, and current September from the mid-1940s to late 1960s. Similarly, park red oak showed a significant positive relationship between radial growth and precipitation for short periods in current June from the mid-1980s to the present,

previous August in the mid to late 1980s, and current March in the late 1920s (Figure 3.5). Street red oak exhibited a significant negative correlation between precipitation and radial growth in current February for a period in the mid to late 1930s, previous November from the late 1890s to the mid-1900s, previous July from the early 1960s to the early 1970s, and previous June from the early to late 1930s and again in previous June from the late 1970s to early 1980s. Street red oak exhibited a positive correlation between precipitation and radial growth in current July in the mid to late 1890s, current June from the early 1890s to early 1910s, current May in the early to late 1930s and again in the early 1940s, current April in the early 1940s, and previous June from the early 1900s to early 1910s before becoming negative later in the 1930s (Figure 3.6)

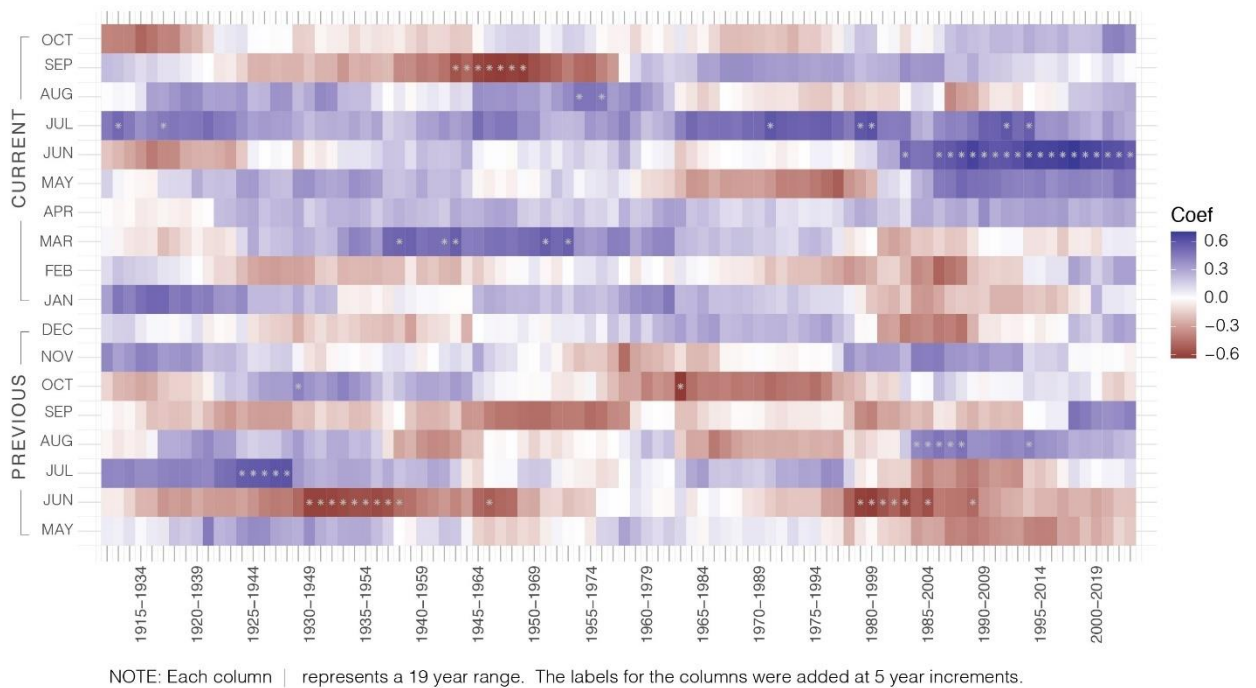
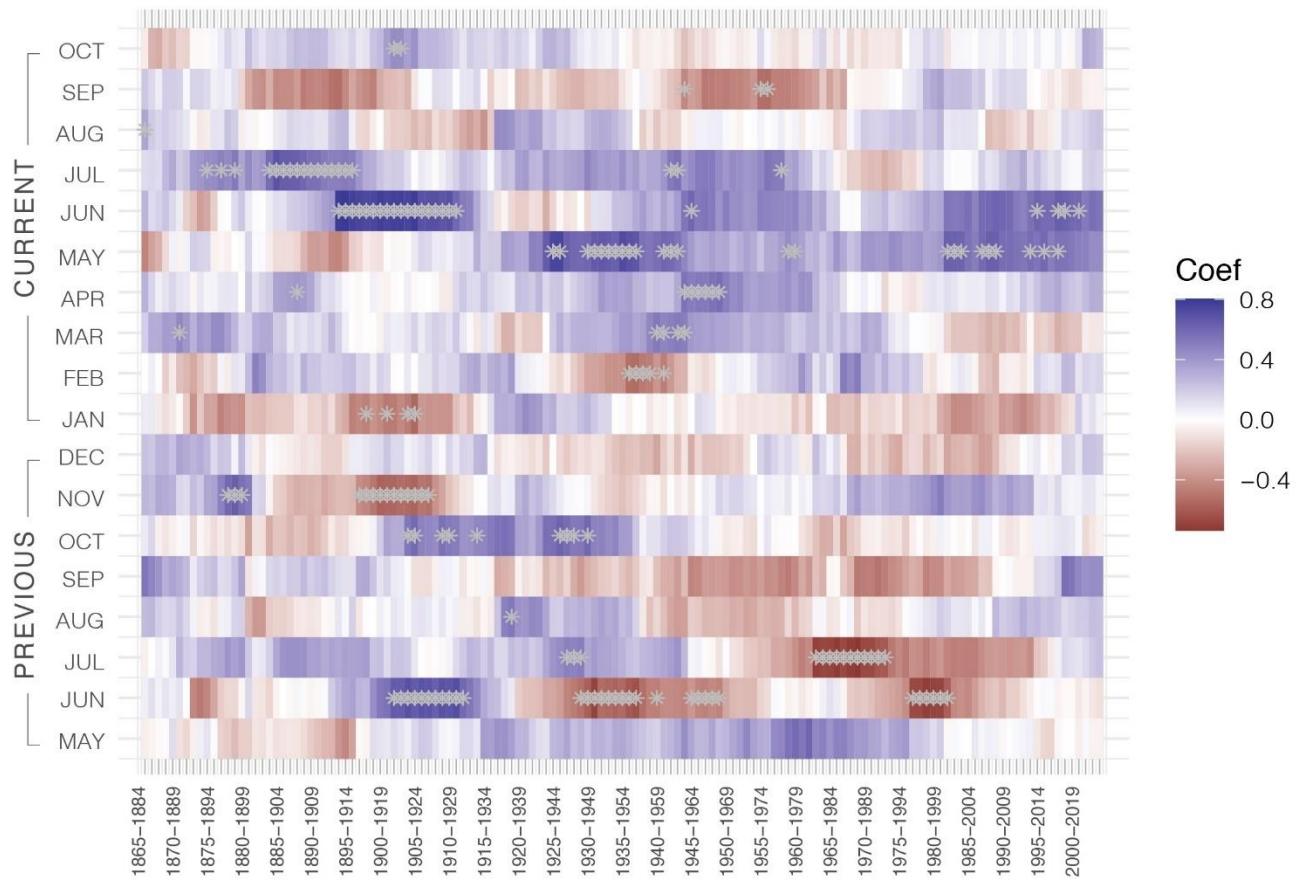


Figure 3.5: Moving climate graph for park red oak and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.



NOTE: Each column | represents a 19 year range. The labels for the columns were added at 5 year increments.

Figure 3.6: Moving climate graph for street red oak and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.3.3 Austrian Pine Response to Precipitation

Sampled Austrian pine in park locations showed a significant ($p < 0.05$) positive relationship between radial growth and precipitation in both previous and current May from the late 1960s to the late 1980s, and a significant ($p < 0.05$) negative relationship between precipitation and radial growth in previous July months from the late 1960s to the early 1980s (Figure 3.7). Street Austrian pine exhibits a significant positive relationship between growth and precipitation in summer months in recent decades, in previous August from the late 1980s to late

2000s, and in current July from the early 1990s to early 2010s. Current January also showed a positive correlation from the late 1960s to mid-1990s, (Figure 3.8).

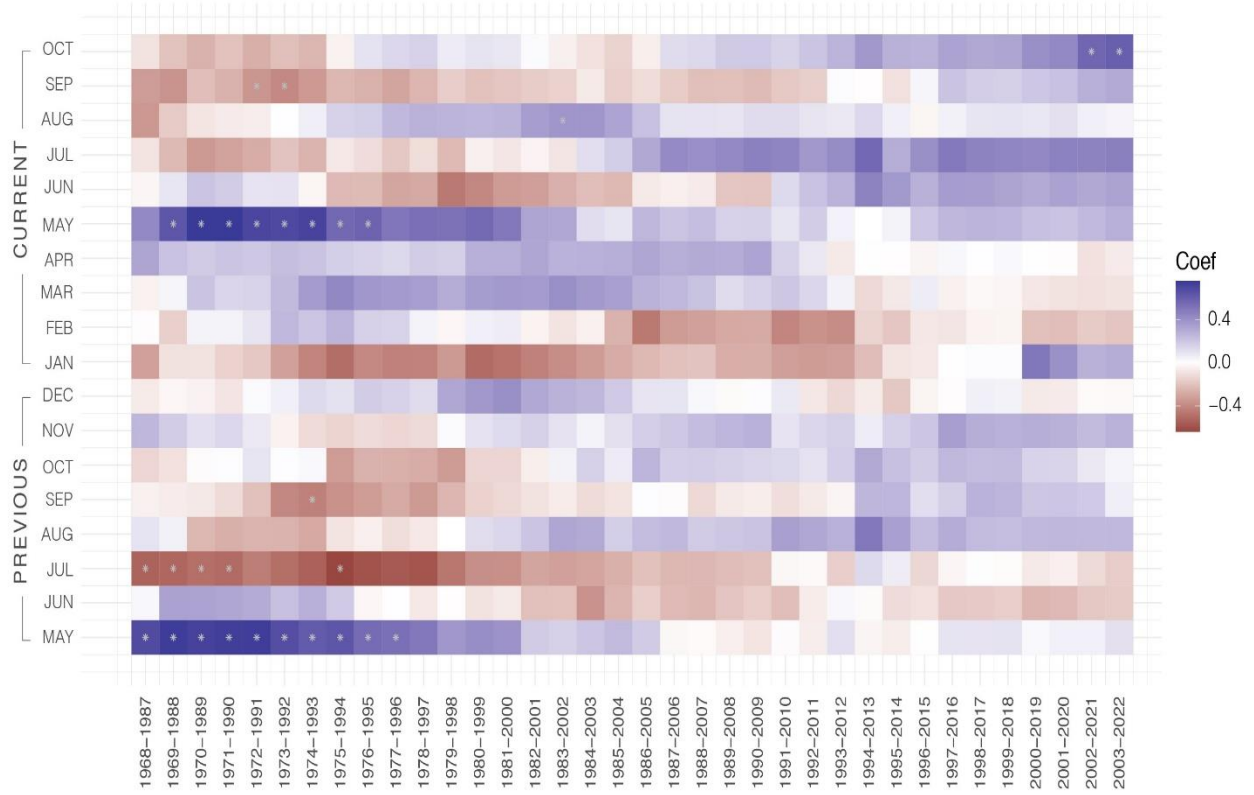
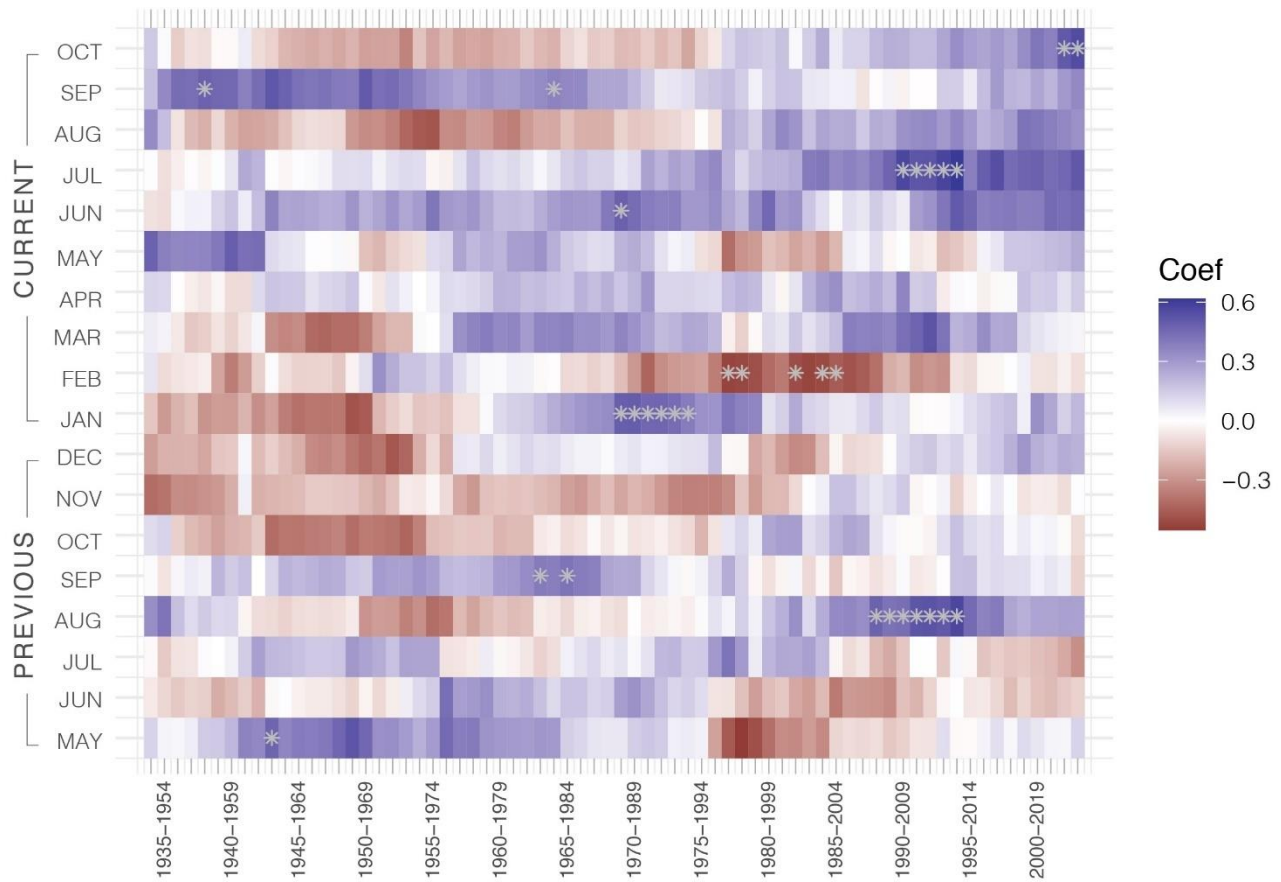


Figure 3.7: Moving climate graph for park Austrian pine and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.



NOTE: Each column represents a 19 year range. The labels for the columns were added at 5 year increments.

Figure 3.8: Moving climate graph for street Austrian pine and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.3.4 Sugar Maple Response to Precipitation

Sampled park sugar maple showed a significant ($p < 0.05$) positive correlation between current August precipitation and radial growth from the early 1990s to the mid-2010s (Figure 3.9). Street sugar maple did not exhibit any significant correlations in the moving plots, save for brief periods of positive correlation in current August in the 1990s, previous December in the 1980s, and previous September in the 1970s (Figure 3.10).

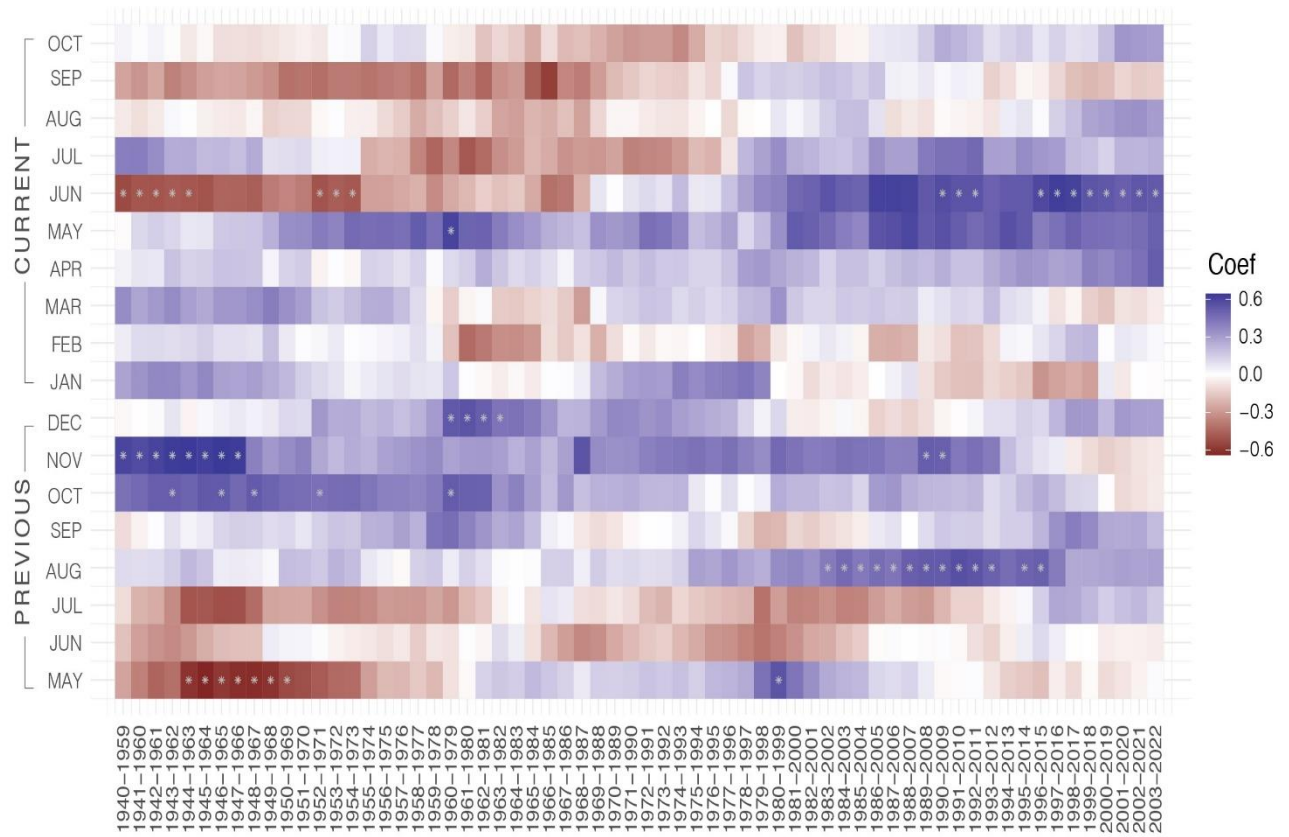


Figure 3.9: Moving climate graph for park sugar maple and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

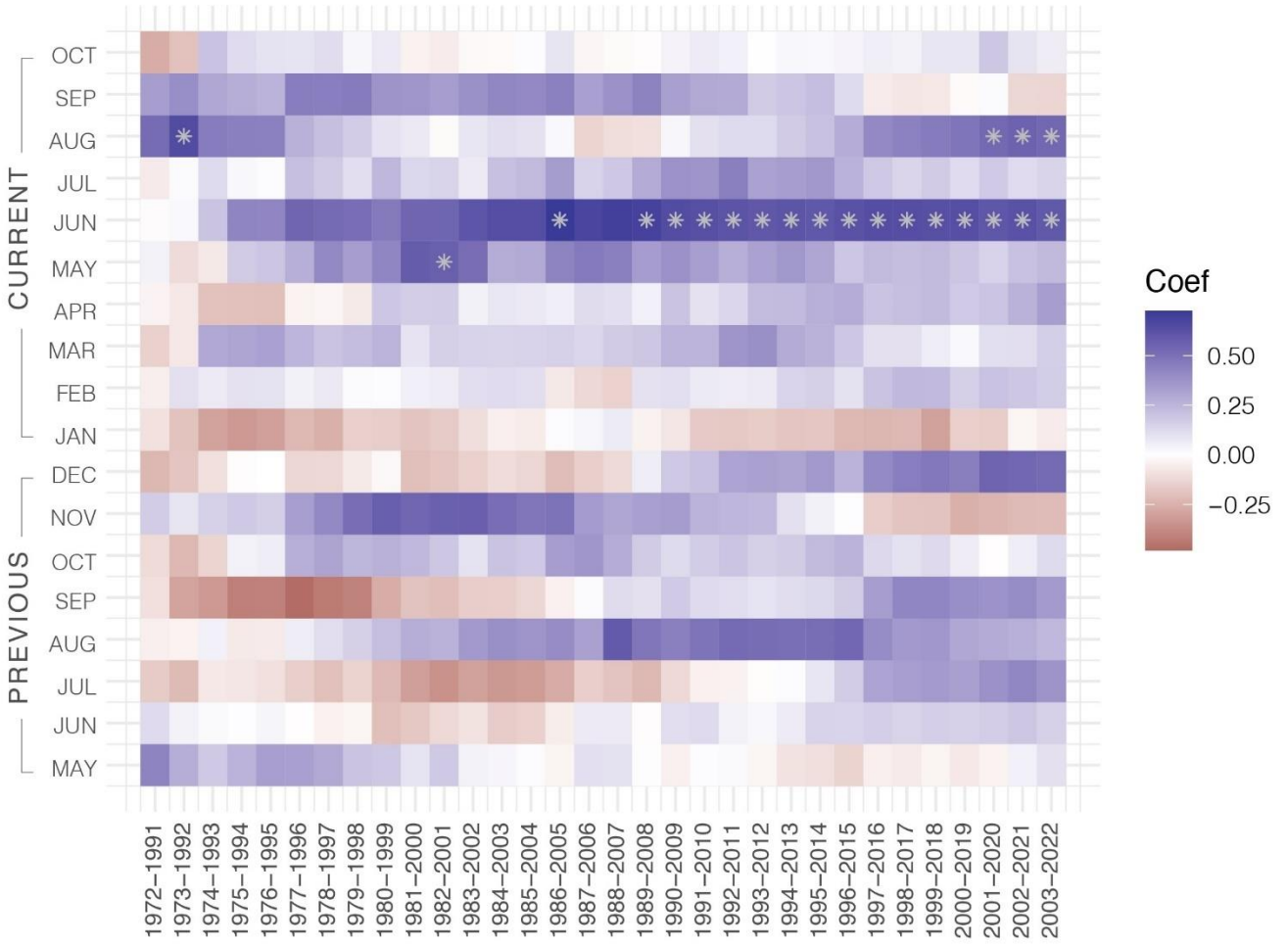


Figure 3.10: Figure Moving climate graph for street sugar maple and monthly mean precipitation.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

Moving Precipitation Analysis Table									
Site-Species	Previous Season				Current Season				Legend
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	
Park Linden	▪	↑	▪	▪	▪	↑	▪	▪	↑ Positive trend
Street Linden	▪	↓	▪	▪	▪	↑	▪	▪	↓ Negative trend
Park Norway Maple	↑	↑	▪	↓	▪	↔	▪	▪	↔ Variable trend
Street Norway Maple	▪	▪	▪	▪	▪	↑	▪	▪	▪ No trend
Park Red Oak	▪	↔	▪	▪	▪	↔	↓	▪	
Street Red Oak	▪	↔	↔	▪	↔	↑	▪	↔	
Park Austrian Pine	↑	▪	▪	▪	↑	↓	▪	▪	
Street Austrian Pine	▪	↑	▪	▪	▪	▪	▪	↔	
Park Sugar Maple	↓	↑	↑	▪	▪	↔	▪	▪	
Street Sugar Maple	▪	▪	▪	▪	▪	↑	▪	▪	

Table 3.4: Summary table of moving precipitation climate-growth analysis

NOTE: Tables are only simplified representations of moving climate-growth correlations, refer to figures 3.1-3.10 for detailed analysis.

3.2.4 Moving Temperature Analysis

3.2.4.1 Linden Response to Temperature

Park and street Linden did not exhibit any prolonged significant periods of correlation between radial growth and temperature in the sampled series (Figure 3.11). Park linden exhibited a period of significant positive correlation between growth and temperature in the previous October months of the late 1970s (Figure 3.11), and street linden exhibited a period of significant negative correlation between growth and temperature in previous July in the late 1960s (Figure 3.12)

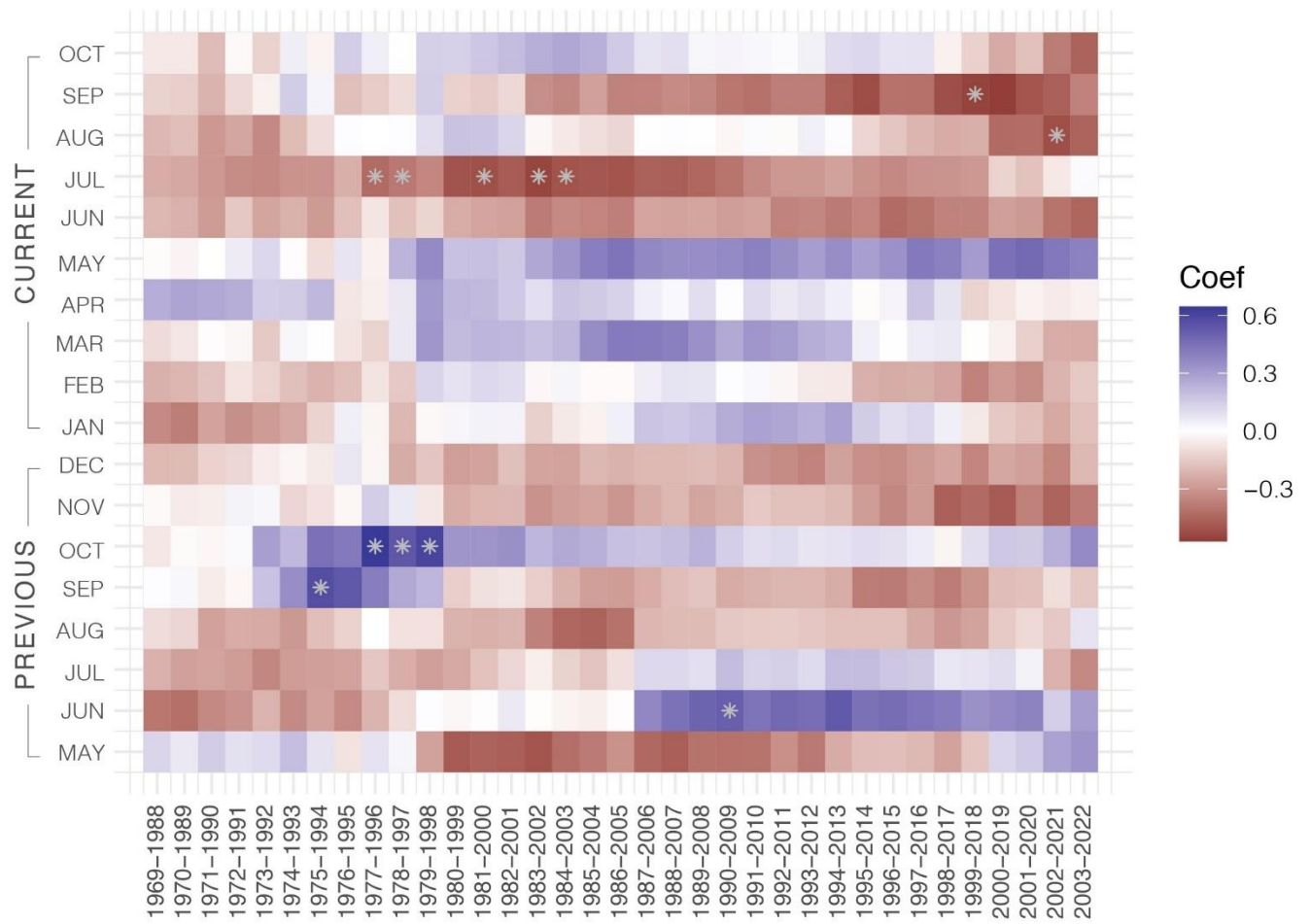


Figure 3.11: Moving climate graph for park linden and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

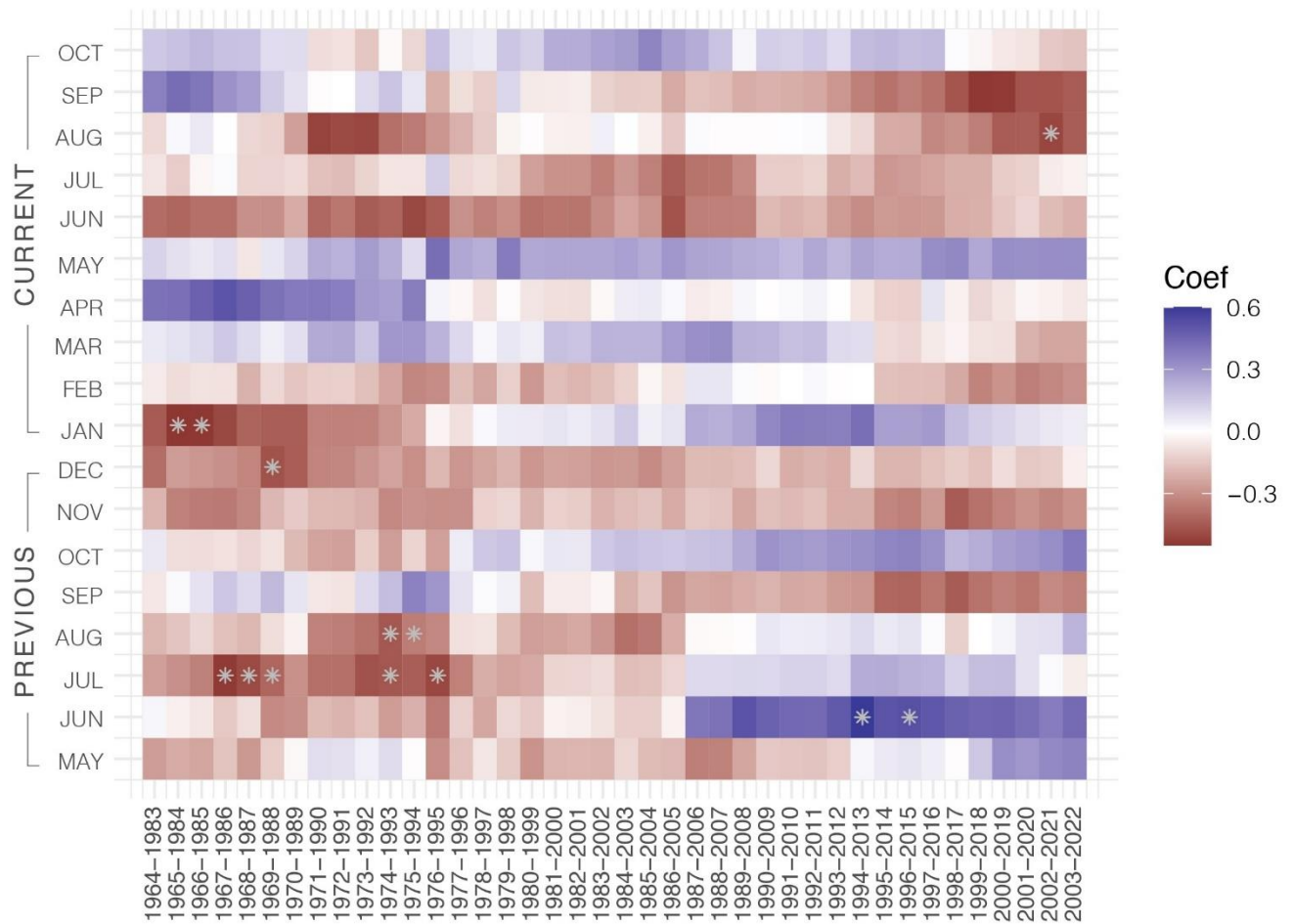


Figure 3.12: Moving climate graph for street linden and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.4.2 Norway Maple Response to Temperature

Park Norway maple exhibits an increasingly significant ($p < 0.05$) negative relationship between radial growth and summer temperatures (current June from the late 1980s, current July from the mid-1990s, and most recently current August to the present) (Figure 3.13). Of note, these summer months had generally exhibited positive correlations (especially August) with radial growth for several decades in the middle of the 20th century. Like park Norway maple, street

Norway maple shows a significant negative relationship between summer (June and July) temperature and radial growth from the early 1980s to the late 2010s (Figure 3.14).

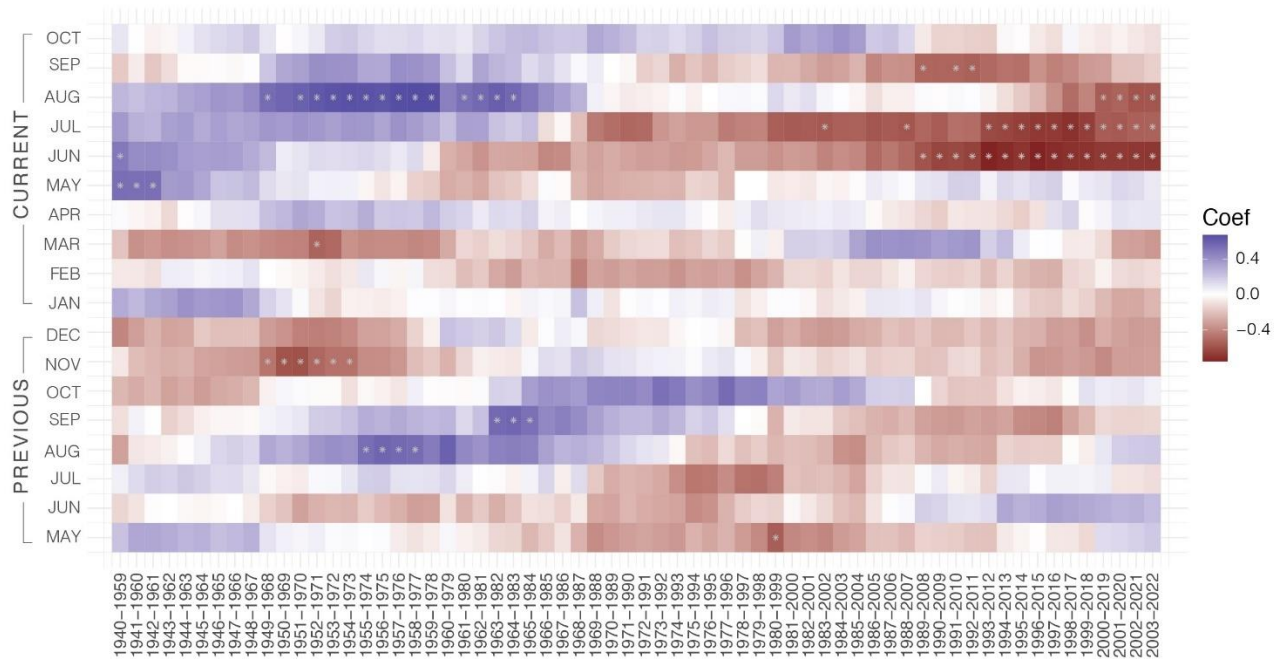


Figure 3.13: Figure Moving climate graph for park Norway maple and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

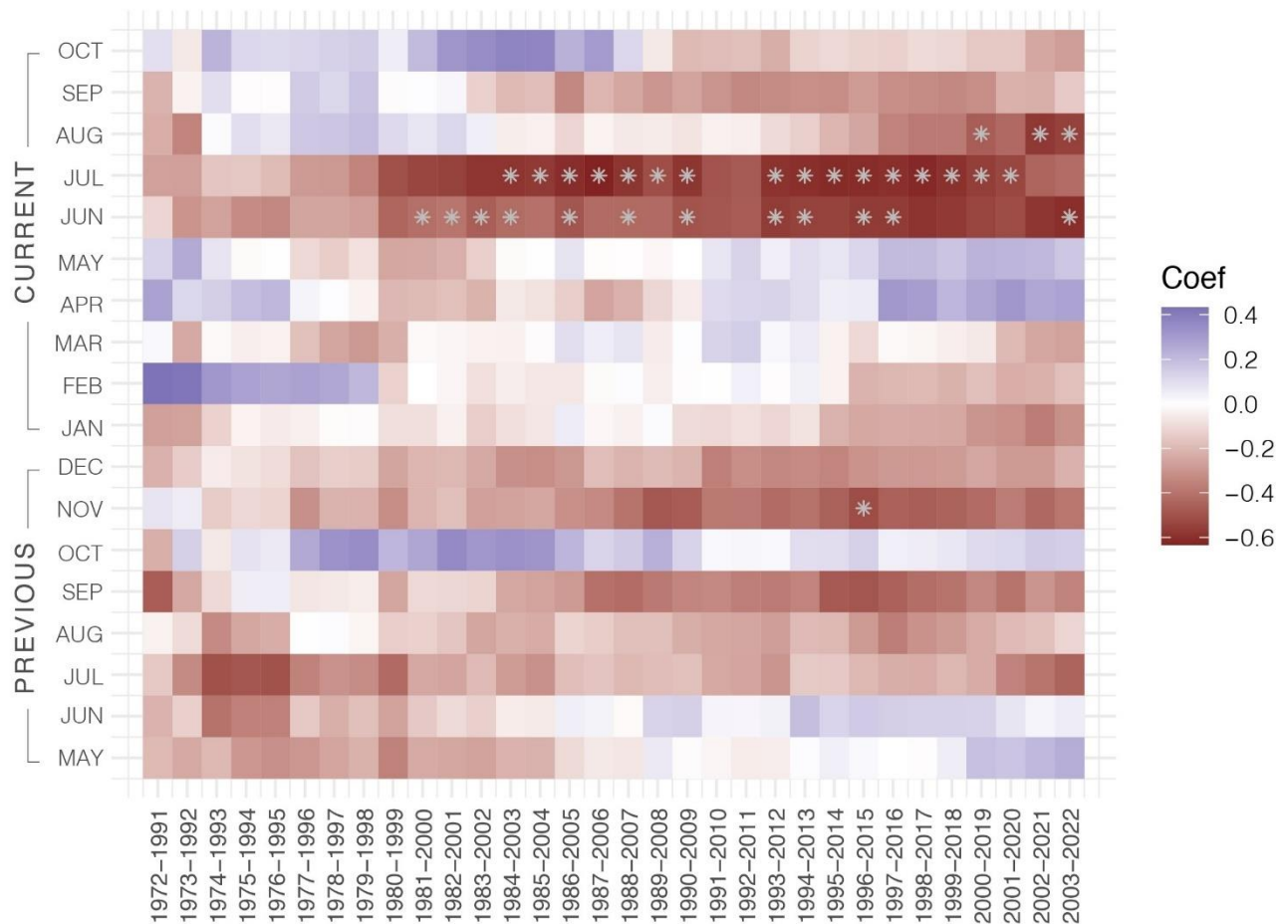


Figure 3.14: Figure Moving climate graph for street Norway maple and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.4.3 Red Oak Response to Temperature

Park red oak showed a significant ($p < 0.05$) negative relationship between radial growth and temperature in current June from the early 1980s to the present, and a positive relationship in current January from the early-1940s to mid-1950s, and previous June from the early 1990s to the present (Figure 3.15). Like park red oak, street red oak exhibited a significant negative relationship between radial growth and current summer temperature (June and July in this case)

generally from the mid-1970s to the present. Unlike park red oak, street red oak has a period of significant positive correlation in previous August from the early 1870s to the early 1880s, as well as shorter-lived significant negative periods for other monthly temperature variables (previous May, August, and current October) (Figure 3.16).

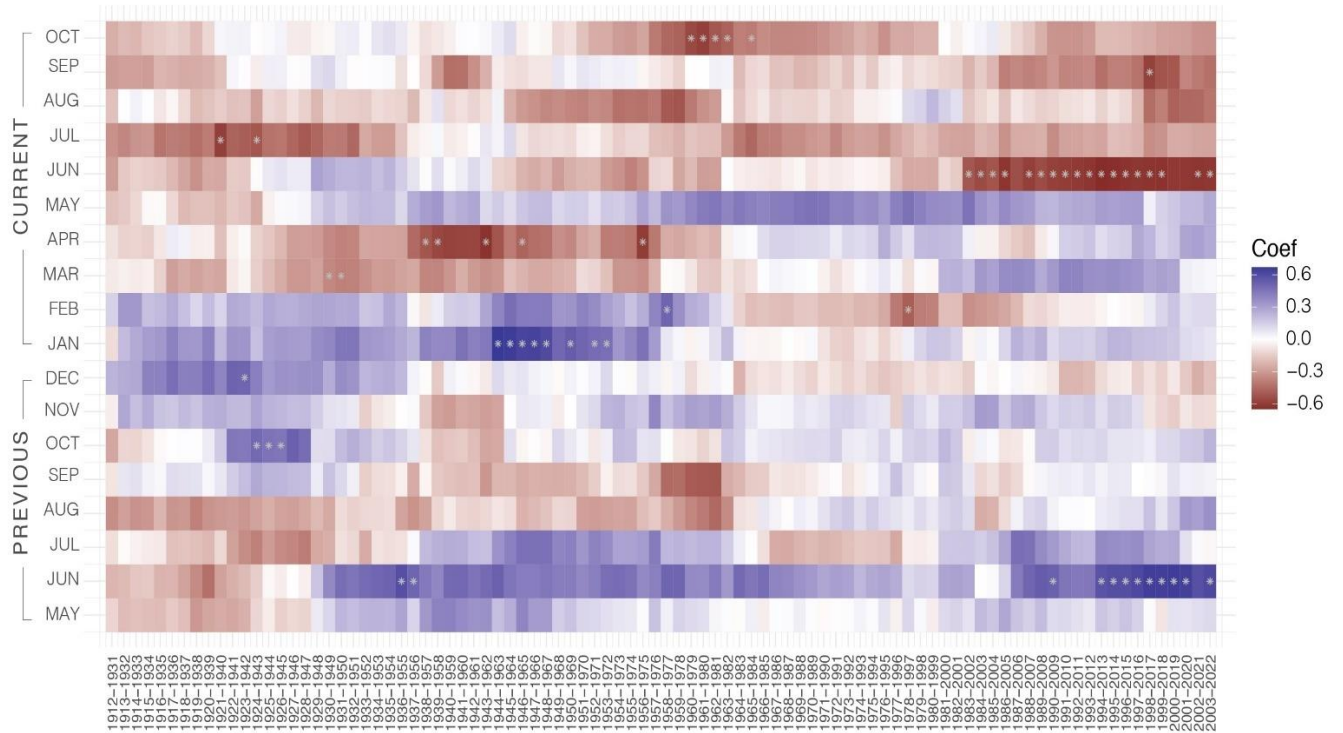
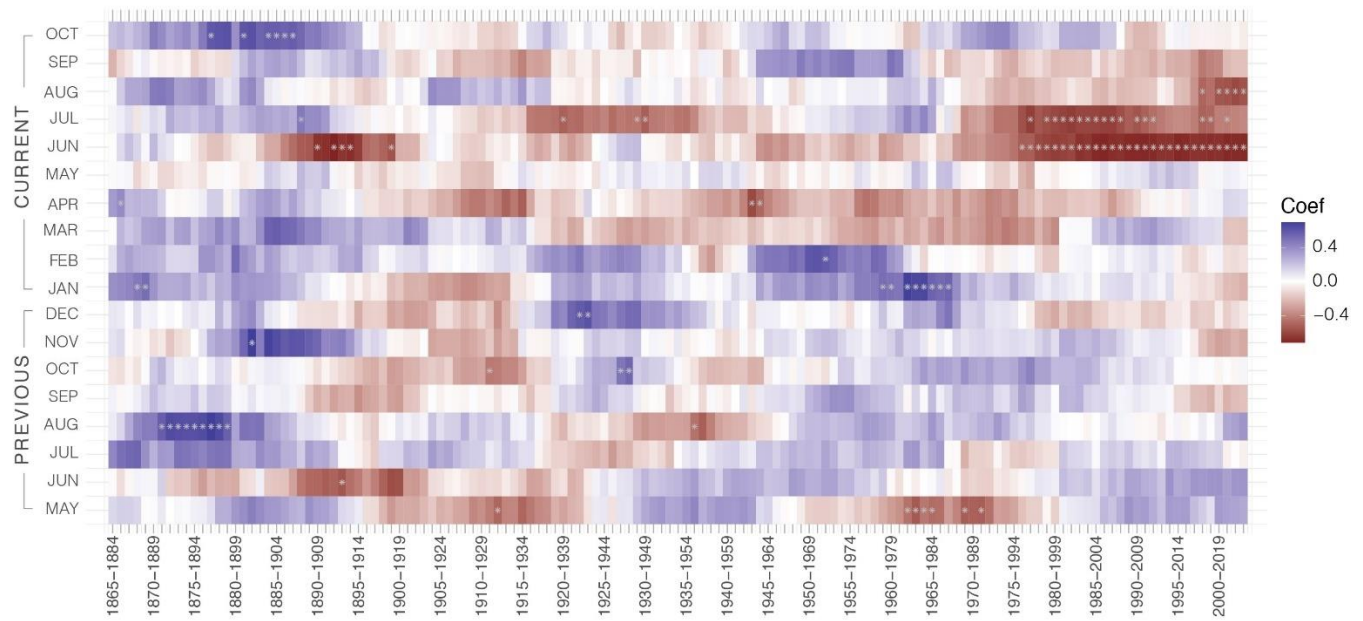


Figure 3.15: Moving climate graph for park red oak and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.



NOTE: Each column | represents a 19 year range. The labels for the columns were added at 5 year increments.

Figure 3.16: Moving climate graph for street red oak and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.4.4 Austrian Pine Response to Temperature

Park Austrian pine showed a general positive relationship with spring temperature, with a significant ($p < 0.05$) positive correlation between radial growth and temperature in current March from the late 1980s to nearly the present. Additionally, there was also a significant positive correlation with previous October temperature for a few years from the late 1970s to early 1980s (Figure 3.17). Similarly, street Austrian pine radial growth was significantly ($p < 0.05$) positively correlated with late-winter and early-spring (February and March) temperature in recent years. Sampled street Austrian pine also exhibited a significant negative relationship between radial growth and temperature in current September from the early 1960s to late 1970s (Figure 3.17Figure 3.18).

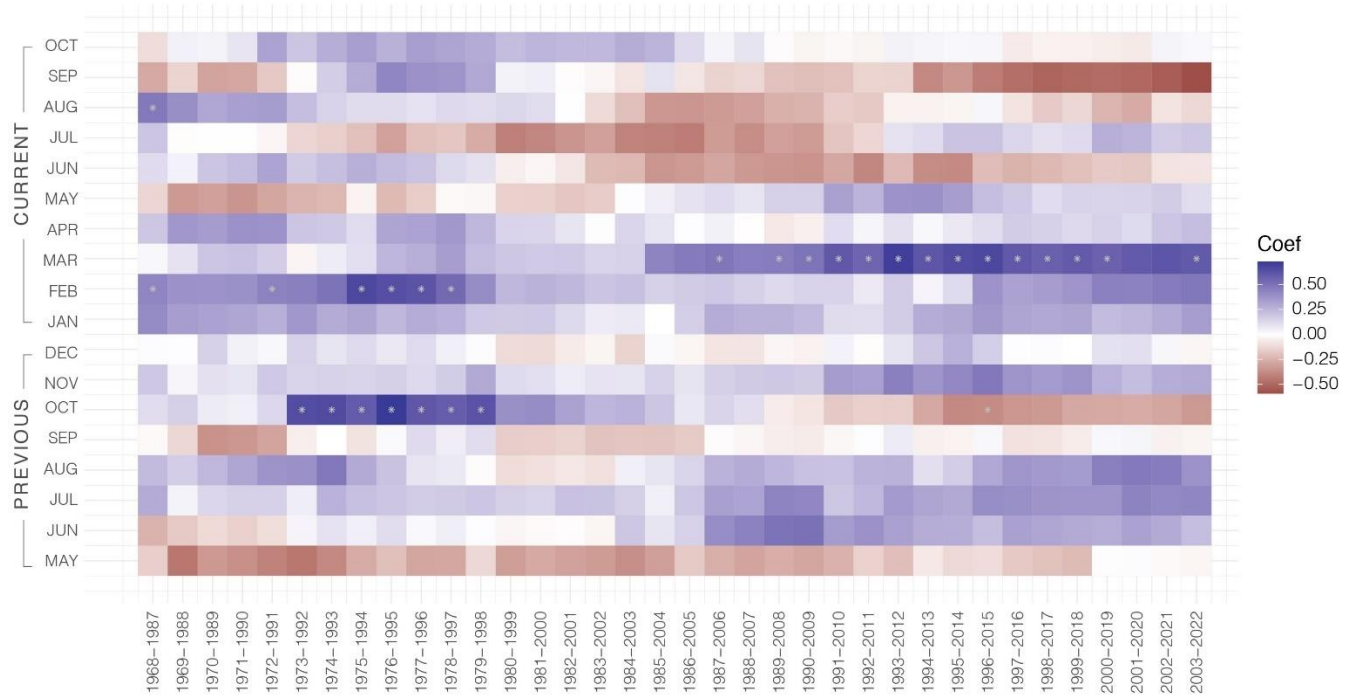
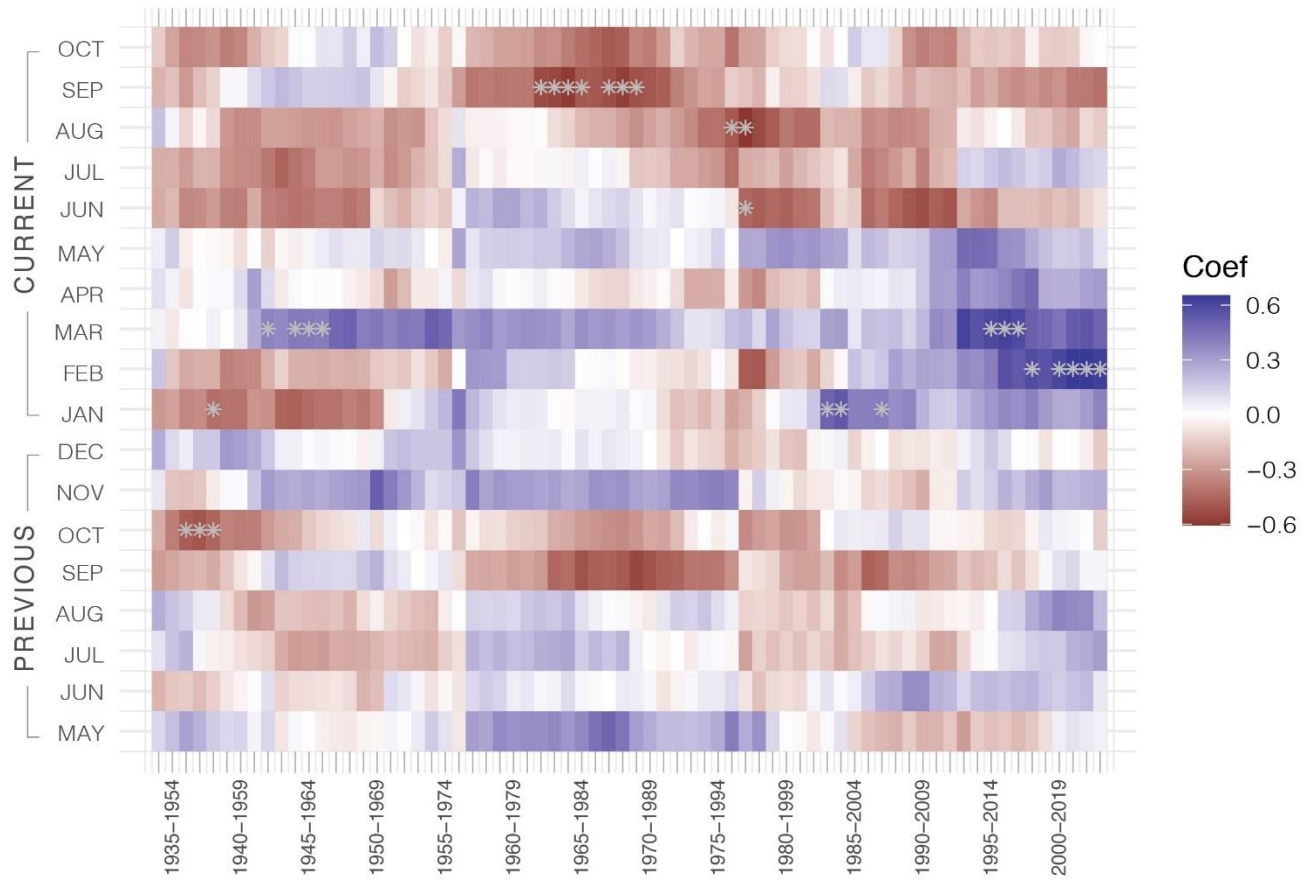


Figure 3.17: Moving climate graph for park Austrian pine and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.



NOTE: Each column represents a 19 year range. The labels for the columns were added at 5 year increments.

Figure 3.18: Moving climate graph for street Austrian pine and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

3.2.4.5 Sugar Maple Response to Temperature

Park sugar maple exhibited a significant ($p < 0.05$) negative relationship between radial growth and temperature in current January from the early 1990s to the present and also in previous summer months (June and July) from late 1980s to the present (Figure 3.19). Similarly, street sugar maple exhibited a significant negative relationship between radial growth and previous summer temperature (June and July) for nearly the entire period of analysis. (Figure 3.20).

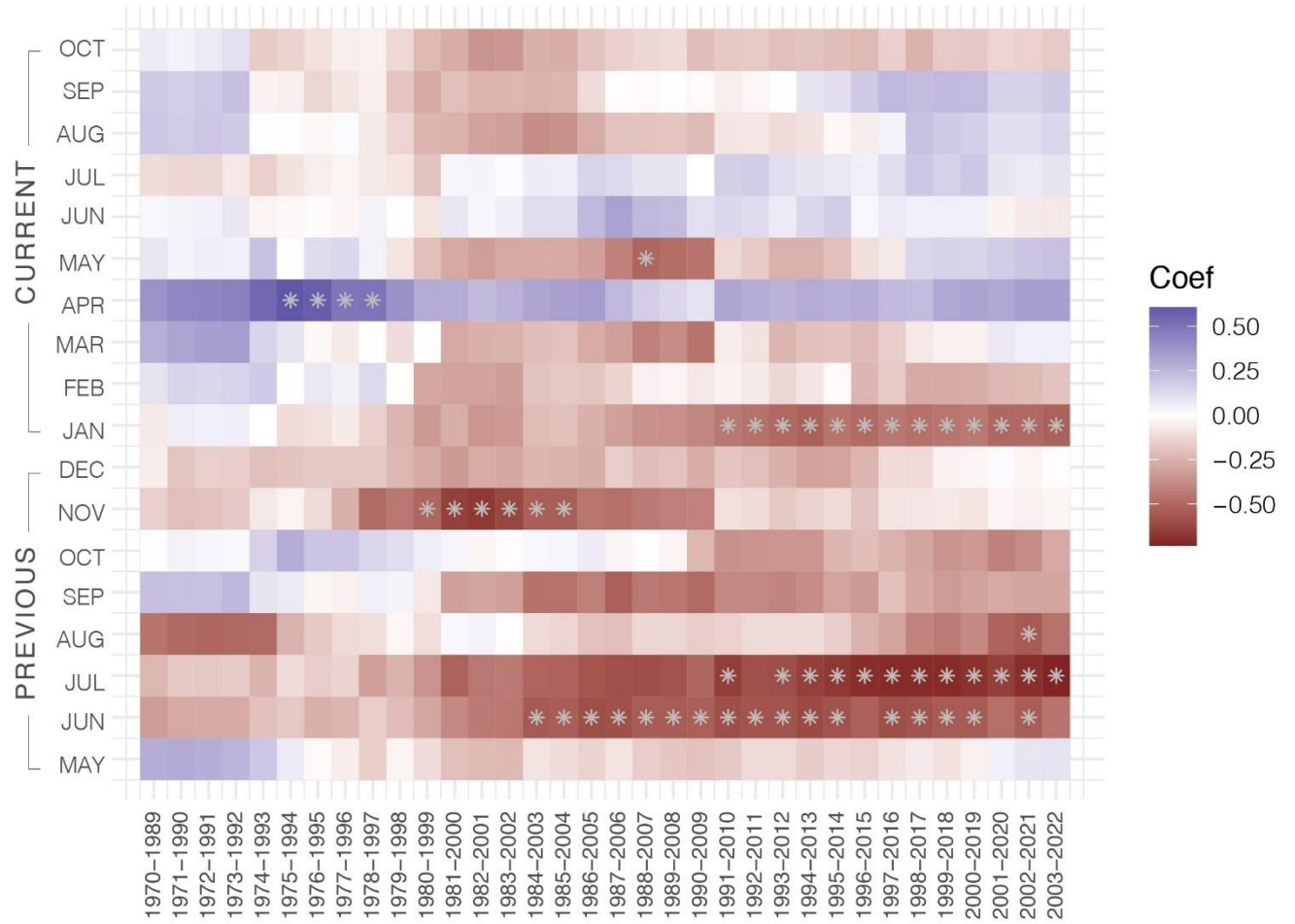


Figure 3.19: Figure Moving climate graph for park sugar maple and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation.

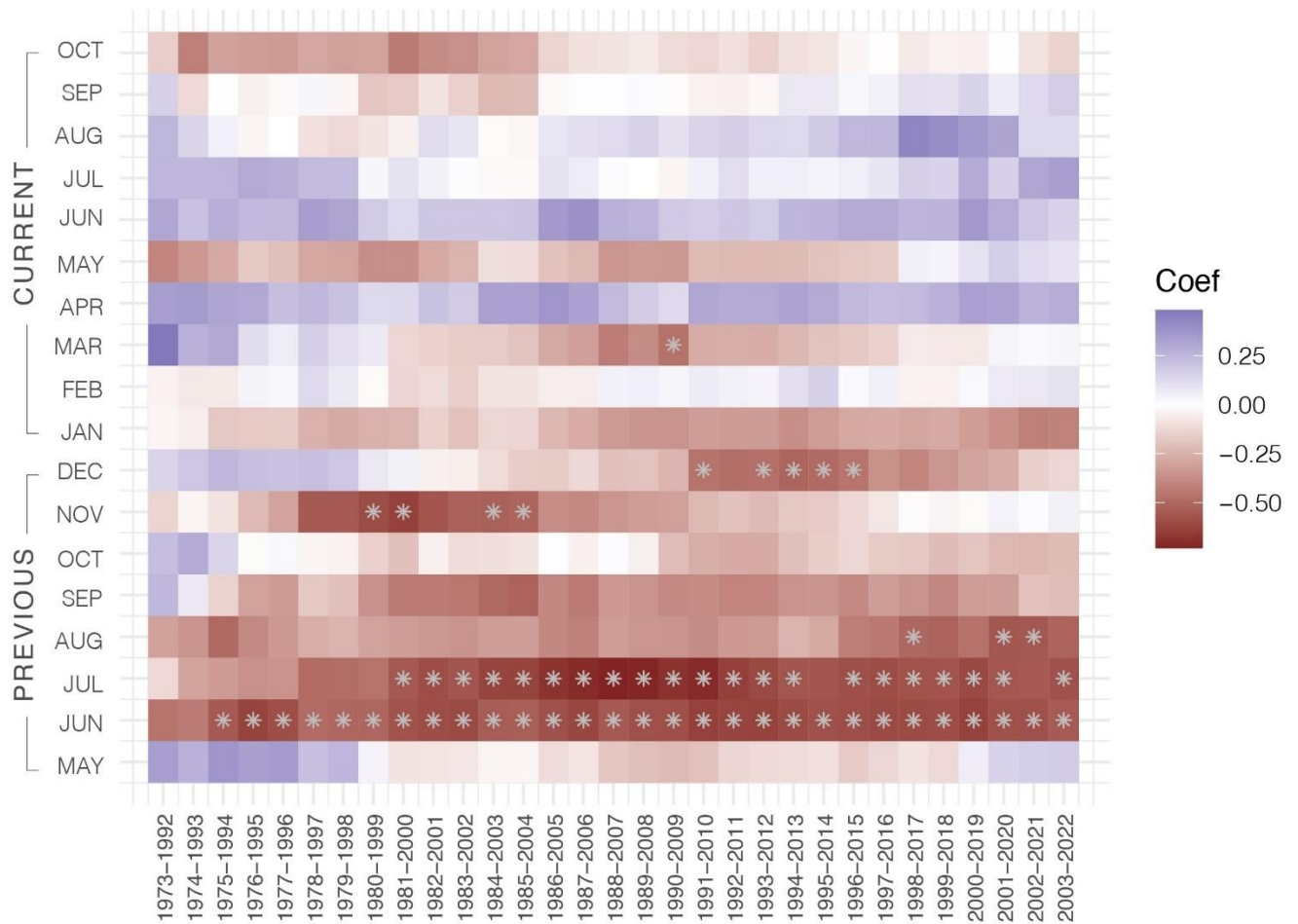


Figure 3.20: Moving climate graph for street sugar maple and monthly mean temperature.

An asterisk * signifies a significant correlation at $p < 0.05$. Blue shaded boxes signify a positive correlation. Red shaded boxes signify a negative correlation. Note, temporal axes are different scales.

Moving Temperature Analysis Table										
Site-Species	Previous Season				Current Season				Legend	
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter		
Park Linden	■	■	↑	■	■	■	■	■	↑	Positive trend
Street Linden	■	↓	■	■	■	■	■	■	↓	Negative trend
Park Norway Maple	■	↑	↓	■	↑	↔	■	■	↔	Variable trend
Street Norway Maple	■	■	■	■	■	↓	■	■	■	■
Park Red Oak	■	↑	■	■	■	↓	↓	↑	↑	
Street Red Oak	↓	↑	■	■	■	↓	↑	↑	↑	
Park Austrian Pine	■	■	↑	■	↑	■	■	↑	↑	
Street Austrian Pine	■	■	↓	■	↑	↓	■	■	■	
Park Sugar Maple	■	↓	■	■	↑	■	■	↓	↓	
Street Sugar Maple	■	↓	↓	↓	■	■	■	■	■	

Table 3.5: Summary table of moving temperature climate-growth analysis.

NOTE: Tables are only simplified representations of moving climate-growth correlations, refer to figures 3.11-3.20 for detailed analysis.

3.3 BAI Analysis

Basal Area Index (BAI) growth rates were examined to both compare species to each other and assess temporal trends in growth rates. As described in the Methods (Section 2.4.5), BAI quantifies annual additions of wood basal area per year (mm^2/yr) (Bunn et al., 2023).

3.3.1 All Trees BAI

The general pattern of all trees BAI growth followed generally the same trends of increases and decreases in growth, though in recent decades there is more than a threefold difference in BAI between the slowest growing species (park and street Austrian pine and street Norway maple) and the fastest growing species (park linden and park oak). Park Norway maple has the highest growth from approximately the 1950s to the 1970s before its growth rates decreases to be similar to that of other species. Austrian pine has generally the lowest BAI increases each year, but this trend only develops in the 1980s, before then Linden in both park and street locations have generally lower growth. Oak in both park and street locations and park linden experience accelerated growth in recent years (Figure 3.21), and street linden growth has also increased since the early 1970s.

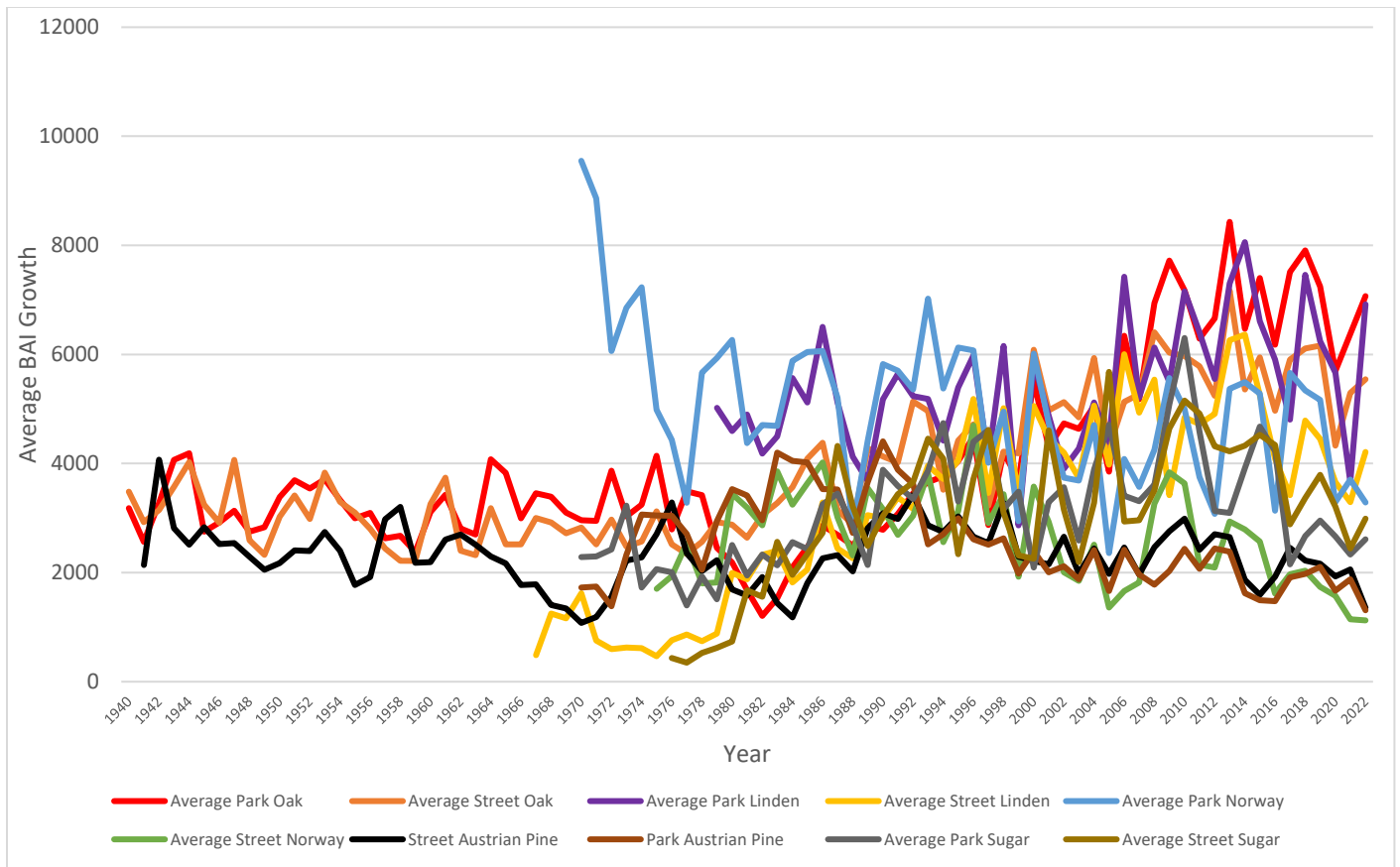


Figure 3.21: Plot of all species and locations average BAI growth per year in mm.

NOTE- Red oak in both locations has been truncated to facilitate temporal comparison with the other species. BAI values are only shown when sample depth reaches three trees.

3.3.2 Segmented BAI Analysis

Like the moving analysis of monthly climate correlations (Section 3.5.2) above, segmented regression (breakpoint) analysis facilitates detection of temporal consistency of growth rates. If a single linear regression line is not the best fit, this analysis determines the year(s) that growth trends change abruptly (breakpoints), and quantifies the growth trend (regression slope) for the different segments.

3.3.2.1 Linden Segmented BAI Analysis

Street linden exhibits a general increase in BAI until the early 2010s before decreasing to the present day. Park linden growth was positive and generally consistent until the late 1990s, when an increase in growth occurs lasting to the present day (Figure 3.22).

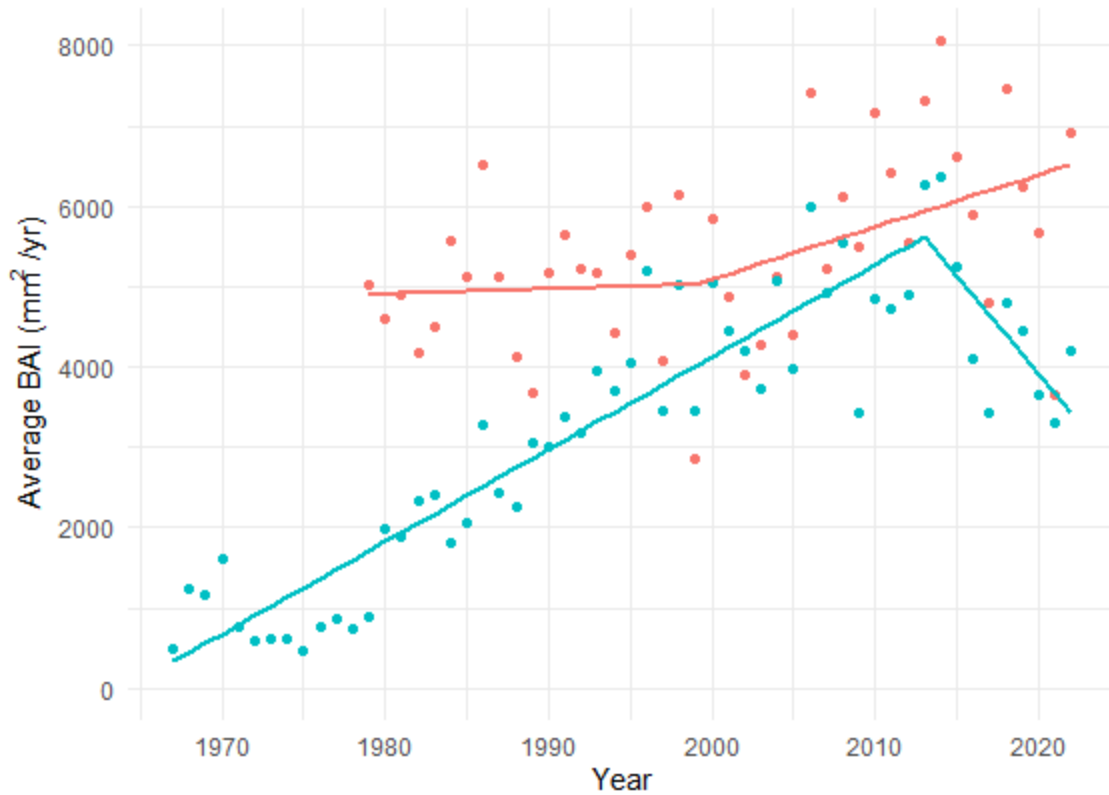


Figure 3.22: Segmented regression plot of linden.

The red line represents park trees, and the blue line represents street trees.

3.3.2.2 Norway Maple Segmented BAI Analysis

Park Norway maple growth was best modeled with a single linear trend for its entire period of growth, and thus a segmented regression was not warranted (Figure 3.23). Street Norway maple exhibited a short period (mid-1970s to mid-1980s) of increasing growth rates before a long steady period of decreasing growth from the mid-1980s to the present (Figure 3.23).

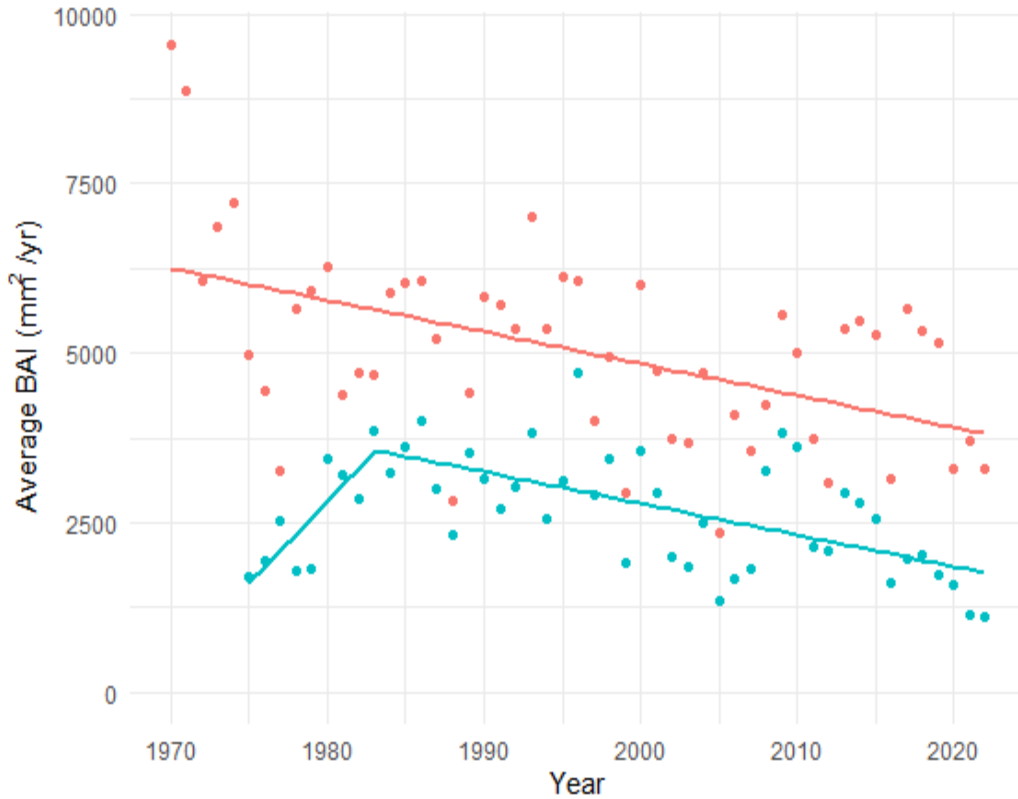


Figure 3.23: Segmented regression plot of Norway maple.

The red line represents park trees, and the blue line represents street trees. (NOTE: a segmented regression was not fitted to park Norway maple as the trend was best explained by a single linear model.)

3.3.2.3 Red Oak Segmented BAI Analysis

The rate of BAI growth of park red oak increased from the late 1900s to 1940s (Figure 3.21). From the 1940s to the mid-1980s both park and street red oak growth rates declined slightly. At approximately the same time, both park and street red oak populations began a prolonged period of increasing growth rates. This period of increasing growth rate has continued for park oak, but street red oak growth rates decline for the last decade (Figure 3.24).

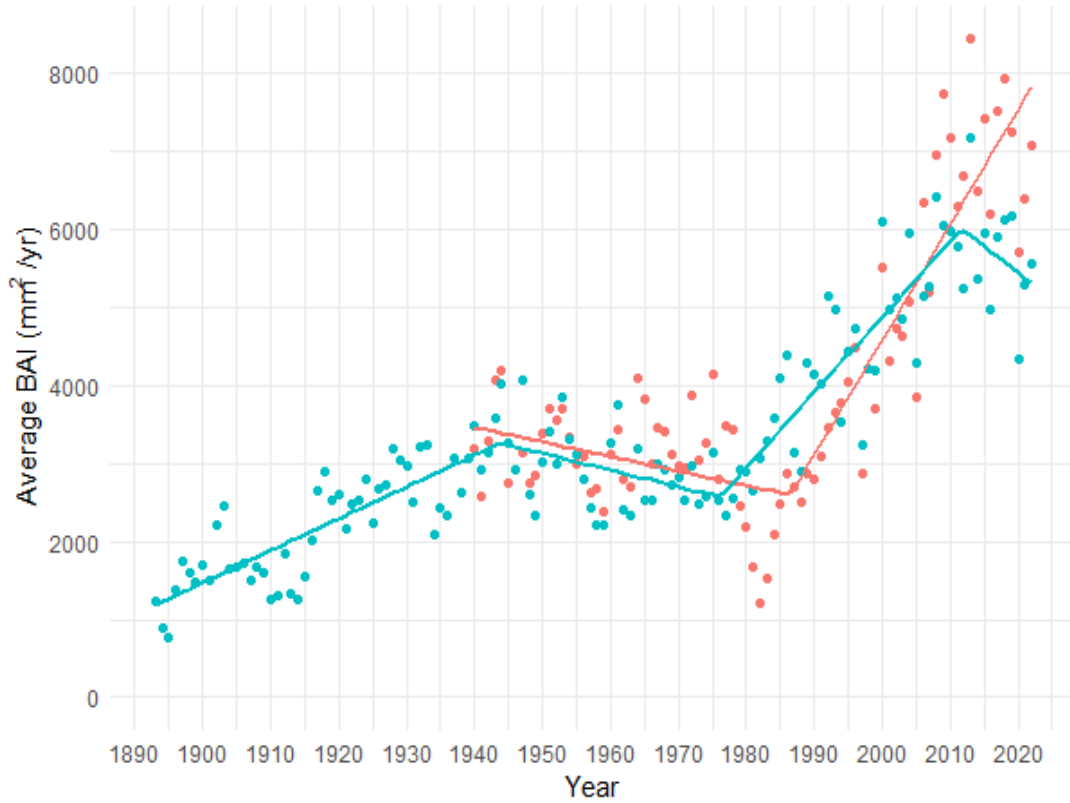


Figure 3.24: Segmented regression plot of red oak.
 The red line represents park trees, and the blue line represents street trees.

3.3.2.4 Austrian Pine Segmented BAI Analysis

Austrian pine in park locations experienced an initial period of increasing growth rates until the mid-1980s, before declining rapidly to the early 2000s, with a slightly slower reduction in growth rate thereafter. Street Austrian pine BAI exhibited declining growth rates from the 1940s to the 1980s, followed by a brief period of increasing growth from the mid-1980s to early 1990s, followed by a decline in growth to the present similar to the park Austrian pine (Figure 3.25).

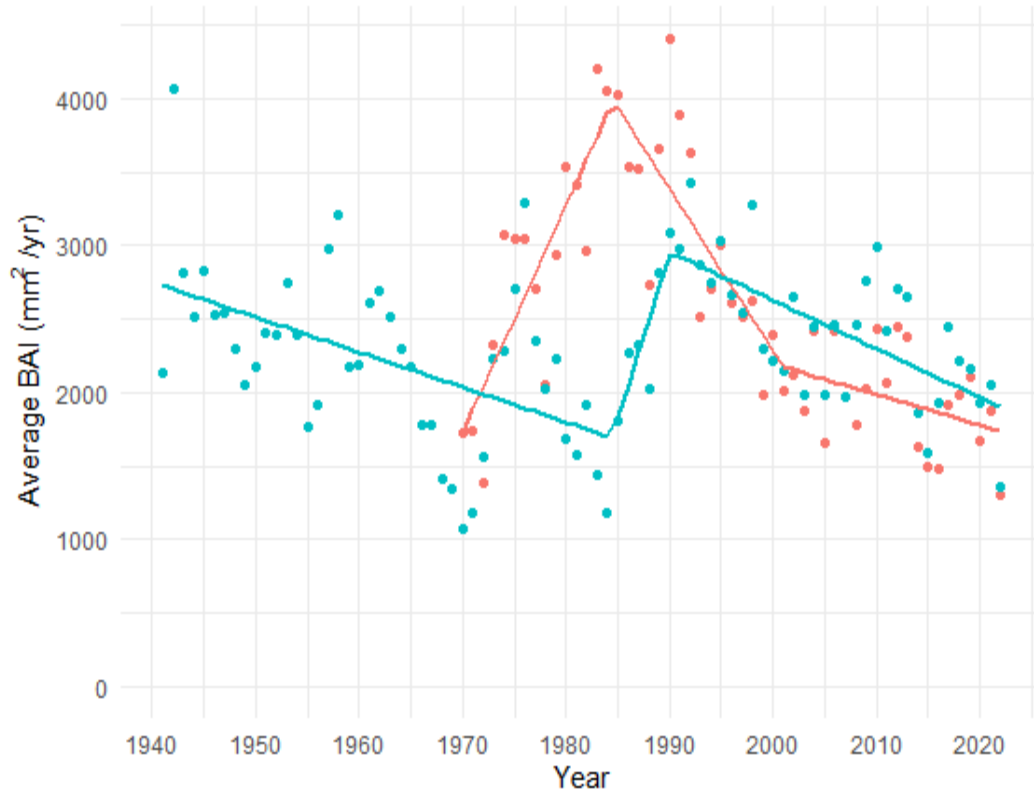


Figure 3.25: Segmented regression plot of Austrian pine.

The red line represents park trees, and the blue line represents street trees.

3.3.2.5 Sugar Maple Segmented BAI Analysis

Both park and street sugar maple show over 40 years of steady positive increases in BAI average growth rate (initially more so for street sugar maple) before growth rates began to decline in the early 2010s, which continues to the present for both populations (Figure 3.26).

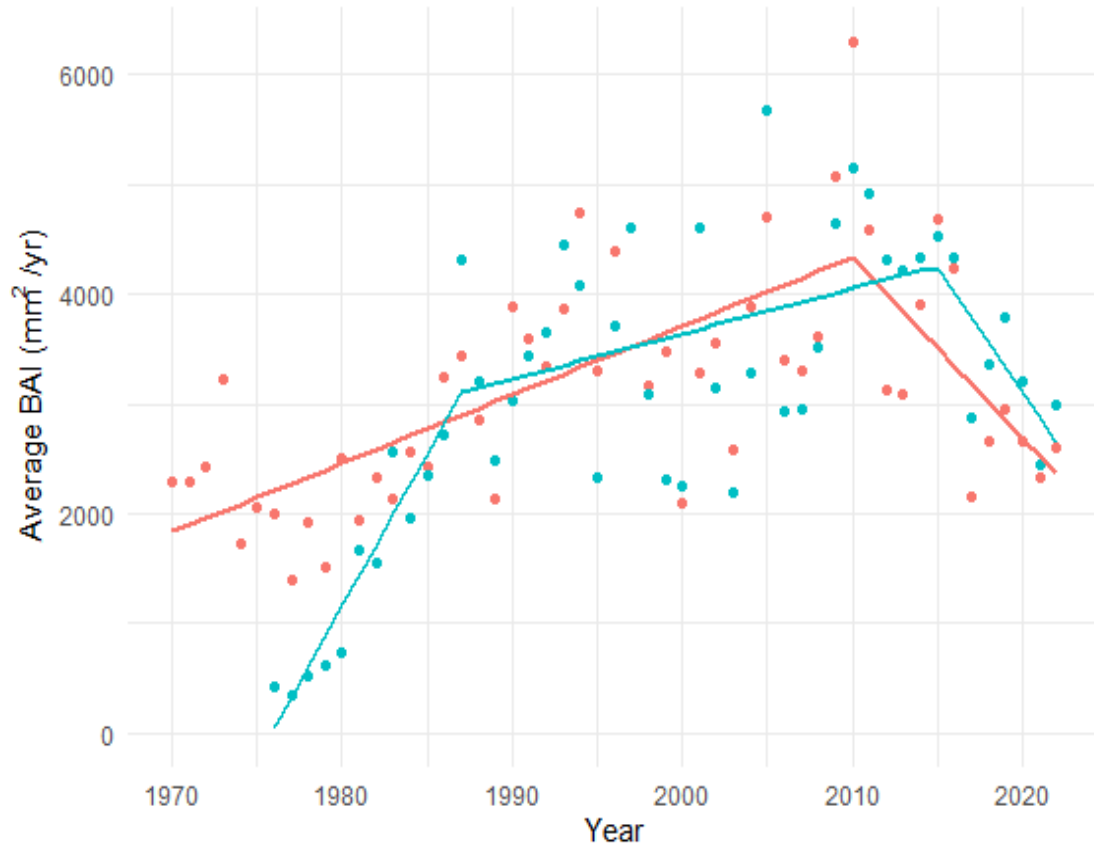


Figure 3.26: Segmented regression plot of sugar maple.

The red line represents park trees and the blue line represents street trees.

3.4 General Patterns

The strongest climate/growth signals were found to be between summer temperature and growth, with most species exhibiting a negative association with summer temperatures, in line with studies in central and eastern European cities that examined deciduous species such as oak, lime, and plane tree (Cedro & Nowak, 2006; Dahlhausen et al., 2018; Helama et al., 2009).

These results are also like studies that have found broadly negative associations between summer temperature and radial growth in North American natural temperate forests (St. George & Ault, 2014; Wettstein et al., 2011). Street trees broadly displayed greater sensitivity to temperature than park trees, in line with research indicating they are more stressed and are likely exposed to greater growth-limiting factors such as impermeable surfaces and anthropogenic pollutants and

irritants, as well as the increased effects of the (UHI) around road surfaces increase heat stress (Ordonez-Barona et al., 2018; Randrup et al., 2001). Some species that had fewer or shorter periods of significant growth-climate correlations, such as sugar maple and Norway maple, displayed a greater sensitivity to temperature than to precipitation in both street and park locations. Linden was the only species that did not display a significant negative correlation between radial growth and temperature.

Strong positive correlations with summer precipitation, found in linden, oak and Norway maples in street locations, indicates that trees in the more stressful street environments are generally water-stressed and exhibit higher growth rates in the wetter summers compared to park trees. Studies in both North America and Europe (David et al., 2018; Hauer et al., 2021; Helama et al., 2009) have found that sugar maples, oaks, and lindens are exhibiting increased water stress in some environments, with linden and oak being particularly stressed by climate in Europe. Less available soil water for street trees is due to impermeable surfaces, such that these trees could be particularly affected by higher urban temperatures, which have increased over the sample period (Government of Canada, 2022) and/or that they are additionally stressed by anthropogenic factors (Mullaney et al., 2015; North et al., 2017; Ordonez-Barona et al., 2018; Randrup et al., 2001).

In both park and street locations, linden and red oak exhibited the highest average annual BAI growth rates in recent decades, but lindens exhibited lower initial growth before trees in both locations began to accelerate their growth in the late 1970s. This could be due to a variety of factors, such as increased summer temperatures, increased access to water (Dahlhausen et al., 2018; De Jaegere et al., 2016; De Roo et al., 2020; Locosselli et al., 2019; Moser et al., 2016), or that the trees likely spent several years in a nursery before being planted. Overall, BAI growth

rates broadly line up with expected trends from the moving and static correlation analyses, with declines detected in BAI growth in recent decades mirroring increasingly negative relationships between summer temperature and radial growth.

Chapter 4 : Discussion

4.1 Species/Growth Trends

4.1.1 Linden

Street Linden radial growth did not correlate with precipitation in the static analysis, but in the moving analysis linden exhibited an increasingly positive correlation with current June precipitation in park locations from the 1970s to late 1990s before disappearing in the early 2000s. Linden also exhibited an increasingly positive relationship with previous August precipitation that also declined in the early 2000s. This departure from positive correlations with precipitation could be a result of the divergence phenomena, which is the phenomenon of trees exhibiting decreased sensitivity to climate variables that in the past have been more strongly associated with annual radial growth trends, despite changing weather conditions which would be expected to improve growth (D'Arrigo et al., 2008; Loehle, 2009). Park linden seemed relatively resistant to precipitation associated stress, however, which is in keeping with studies of linden in natural and urban areas (De Jaegere et al., 2016; Martynova et al., 2020)

Park linden also did not correlate with temperature in the static analysis and had only limited periods of significance in the moving analysis, notably in the late 1970s. This indicates the species may be benefitting or at the least not being significantly harmed by high temperatures in Toronto parks, as the species has displayed a high tolerance for a variety of climates in studies in Europe, and generally grows in warmer climates in its native European range than the climate in southern Ontario (De Jaegere et al., 2016; Pretzsch et al., 2017). Like its park counterpart, street linden did not correlate with precipitation in the static analysis but did display an increasingly positive relationship with current June precipitation from the mid-1970s to early-2000s before becoming insignificant thereafter. Street linden, unlike its park counterpart, does

display a period of negative correlation between growth and precipitation between the mid-1980s and early 2010s. This could be due to a lack of rainwater penetration in street growing locations due to the prevalence of impermeable surfaces (Gregg et al., 2003; Locosselli et al., 2019; Randrup et al., 2001), or could also be a signal of the divergence phenomena (D'Arrigo et al., 2008). Street linden displayed a negative correlation between temperature and growth for current June in the static correlation, but otherwise did not display a major sensitivity to heat unlike many of the other sampled species. Similar to its park counterpart, this resiliency to summer heat could be a result of the species mostly growing in warmer climates in its native range in Europe (De Jaegere et al., 2016) and could also be indicative of the hardiness of the species, which has been demonstrated in Europe (Martynova et al., 2020; Pretzsch et al., 2017).

Linden displayed a difference in overall growth trends in the BAI analysis between park and street locations. While both park and street linden had relatively high annual BAI growth, street linden growth has slowed in recent years, while park linden has increased. The species is likely experiencing greater stress in street locations due to the prevalence of impermeable surfaces and anthropogenic pollutants, which are increasing as the city expands (Equiza et al., 2017; Locosselli et al., 2019; Oke, 1973; Ordonez-Barona et al., 2018). Overall, however, linden displays a notable tolerance to the urban climate, which is exemplified in the segmented analysis, which shows park linden had a positive growth trend in the past 20 years. The BAI growth of linden mirrors its growth/climate correlations in the moving and static correlation analyses, which found the species to be relatively immune to physiological stress by summer temperatures, while benefitting from summer precipitation. Although street linden has exhibited a decline in BAI growth since 2010, the species still displays overall positive trend, which is in keeping with studies from Europe and Asia which found *Tilia* species to be resistant to urban climate and to

many environmental stressors, such as summer heat (David et al., 2018; De Jaegere et al., 2016). Linden's BAI growth trends line up with the climate correlations, which have found some stressors in recent years, particularly for the street, but still exhibiting strong growth.

4.1.2 Red Oak

Park red oak was the only species/location that displayed a negative correlation with previous June precipitation in the static correlation analysis. This negative correlation over the growing period has shifted to a positive correlation in recent years however, suggesting that increased summer temperatures could be increasing heat stress on red oak and thus making precipitation more vital to growth, which is supported by studies that have found oak to be heat-stressed in cities (Helama et al., 2009; Thomsen et al., 2020) as well as studies that suggest generally greater heat stress on trees in urban areas in recent decades (North et al., 2017; Randrup et al., 2001). Red oak's susceptibility to drought is in line with other studies (Helama et al., 2009; Jenkins & Pallardy, 1995), which have indicated the species is more sensitive to drought in summer months in temperate environments than some other hardwoods (Bahe et al., 2021).

Street and park red oak both exhibit increasingly negative relationships in recent decades with current growing season summer temperature, however the effect is less pronounced in the park, and indeed street red oak even exhibits an increasingly positive relationship with previous June temperature, indicating that street red oaks may benefit from higher temperatures. This contrasts with park red oaks, which display periods of negative correlation to previous year summer and spring temperatures and increasingly negative correlations between temperature and growth in several summer months. This trend is the reverse of the other species in this study, which display greater stress in street trees, which could indicate that red oaks are particularly

well adapted and are more tolerant of certain anthropogenic factors in cities, such as CO₂ emissions (Nowak et al., 2006; Pretzsch et al., 2017; Sonti et al., 2019).

In both street and park locations red oak has some of the highest average BAI growth for all species, with park oak exhibiting particularly strong growth. Street red oak does exhibit a recent decline in growth in the segmented analysis, in line with the moving correlation analysis showing an increasingly negative association between summer temperature and growth. Despite this recent decline in BAI growth rates, it continues to have one of the highest average BAI growth rates of all sampled species. The continued high BAI values suggests that precipitation is a more important limiting factor in growth than temperature, at least for the present. Red oak's continued high growth rate is in despite of it having the oldest sampled specimens in the study, and most sampled trees being older than the other species. Red oak's strong growth could be indicative of a positive response to the urban environment, such as from exposure to elevated CO₂ (Locosselli et al., 2019; Pretzsch et al., 2017), and benefitting from warmer temperatures (Nowak et al., 2006; Pretzsch et al., 2017; Sonti et al., 2019). The species also grows a deep root system, which could be make the species especially drought tolerant particularly in park locations where it often has a larger area for potential root growth, unlike in street locations where root growth is more restricted (Randrup et al., 2001). Southern Ontario is also one of the northernmost extents of red oak's natural range, and thus the warmer urban climate could be accelerating the species growth through the artificial creation of more favorable environments (Pretzsch et al., 2017).

4.1.3 Austrian Pine

Austrian pine growth exhibited little correlation with precipitation, the only notable relationship was with street Austrian pine exhibiting a positive correlation with current

September precipitation, possibly indicating the street locations are more water-stressed than park locations (North et al., 2017; Ordonez-Barona et al., 2018), particularly in late-summer. The moving analysis reveals that both locations have experienced periods of positive and negative correlation with precipitation, mostly in current and previous spring and summer months. These trends suggest that Austrian pine is relatively drought tolerant, which is supported by another North American study finding the species to be drought tolerant (Leege & Murphy, 2000). However, this drought tolerance could be reduced with exposure to other stressors, such as increased temperature stress, as found in its native range (Manrique-Alba et al., 2021).

Austrian pine exhibited was the only species sampled with a positive correlation between temperature and growth in the static correlation analysis, with park Austrian pine exhibiting a positive relationship between current January temperature and growth. The moving correlation analysis additionally shows an increasingly positive relationship with current season late winter/early spring temperature, indicating that the species could be responding well to warmer winter temperatures. Austrian pine is naturally found in generally warm Mediterranean environments; thus, the milder winter temperatures could benefit the species in Toronto (Manrique-Alba et al., 2021).

Austrian pine BAI growth rates were relatively low. Despite park and street locations exhibiting an increase in growth rates in the 1970s and 1980s in the segmented analysis, both park and street have shown declines recently. Austrian pine is a non-native species and is naturally found in warmer and drier conditions in southern Europe (Manrique-Alba et al., 2021), suggesting the species, while drought and heat tolerant, may not be well suited to the cooler and wetter environment of southern Ontario (Leege & Murphy, 2000; Manrique-Alba et al., 2021; Wang et al., 2019). It is also a long-lived species (Leege & Murphy, 2000; Manrique-Alba et al.,

2021), and given that it is the only evergreen species sampled in this study, a comparison of its BAI growth rates to deciduous species is not without caveats.

4.1.4 Sugar Maple

Sugar maple displayed a positive correlation with current year summer precipitation in both sample locations, a pattern supported by studies conducted in North America that have also found the species to be sensitive to precipitation and drought (Mulozi et al., 2023; Rudolph & LeBlanc, 2020). The moving analysis revealed the species has not had any significant periods of negative correlation with precipitation, and only smaller periods of positive correlation with precipitation other than previous summer (e.g. park sugar maple exhibiting a positive correlation with current August precipitation). This could also be due to the relatively young age of the sampled trees, which in both locations only had ages dating back to the 1970s.

Sugar maple exhibits a significant negative relationship between the previous season's summer temperature and growth in both street and park locations. While both sites exhibit negative correlations with summer temperatures, park sugar maple also exhibits an increasingly negative relationship with current January temperature, indicating that higher winter temperatures could be stressing park trees more than street trees.

Sugar maple displayed mid-range BAI growth rates, with both street and park locations exhibiting strong early growth before declining in recent years. Both locations' growth patterns were similar, with park having a longer period of sustained strong growth than street, suggesting initial stress in street locations. The decline in BAI growth aligns with its growth/climate correlations, which found the species to be particularly sensitive to summer heat, an effect which was shown to be increasing in recent decades in the moving analysis. Both species notable decline in recent years is likely due to increased heat stress, with street locations likely to

experience greater heat stress in coming years due to more shallow root systems (Dahlhausen et al., 2018; Randrup et al., 2001; Teskey et al., 2015).

4.1.5 Norway Maple

Park Norway maple displayed a positive relationship with previous October and November precipitation for the entire period of record. The positive association with previous year fall precipitation could be due to Norway maple's generally higher resistance to drought (Lazic et al., 2022). Street Norway maple does not exhibit this same response to previous fall precipitation, but does show a positive relationship with current year June precipitation, which could be indicative of street trees having many more impermeable surfaces around its root systems, limiting its water intake (Randrup et al., 2001; Wyckoff & Webb, 1996), as well as research from Europe indicating that some deciduous street trees are particularly sensitive to fall precipitation due to the effects of the urban environment, such as the prevalence of impermeable surfaces (David et al., 2018).

Both street and park Norway maple exhibit an increasingly negative relationship with current growing season summer temperature and growth in the past 40-50 years, with the trend showing earlier in the series (late 1970s-1980s) for street than for park trees. Unlike linden, Norway maple is showing increased stress from summer temperatures, suggesting further declines in growth are likely if the urban climate continues to warm (Locosselli et al., 2019; Teskey et al., 2015). These declines are generally in line with studies in Europe, which has found the species to be harmed by drier and warmer summers (Zimmermann et al., 2015).

Park Norway maple displayed low BAI growth rates, with street Norway maple having some of the lowest average BAI rates of the species studied, and park Norway maple exhibiting a notable decline in recent years. In the segmented analysis, park Norway maple exhibited a

negative growth trend for the entire sampled period and street Norway maple's growth decline occurring not long after its initial increase. This suggests that Norway maple in both sample locations is experiencing significant and increasing stress in urban environments. This is reinforced by the results of the moving and static analysis, which found both street and park Norway maple to be increasing summer heat stress in recent years. Norway maple is a commonly planted street species, and despite its native European range having a comparable climate to southern Ontario (Wyckoff & Webb, 1996), the species exhibited high stress in this study. This could be due to increased water stress from growing in the urban environment, as the species has relatively shallow roots and could be struggling to receive enough water, as well as being exposed to anthropogenic pollutants (Randrup et al., 2001; Teskey et al., 2015).

4.2 Potential Future Changes

The climate of southern Ontario and of Toronto is expected to get warmer and wetter over the coming century because of anthropogenic climate change (Lemieux et al., 2005; Wang et al., 2016), which will create and amplify stressors for urban trees in some species while enhancing growth for others.

4.2.1 Trees Well-Adapted to Toronto's Urban Climate

Linden is likely to adapt well to the changing climate, as it has been shown to be a hardy and adaptable species in studies in Europe and Asia (Martynova et al., 2020; Moser-Reischl et al., 2019; Pretzsch et al., 2017). The species exhibited greater tolerance to summer heat than other species in this study, in line with studies in Europe which have shown it to be drought tolerant (David et al., 2018; De Jaegere et al., 2016). Despite linden showing a decrease in growth in street locations in the past decade in the segmented BAI analysis, it remained one of the more vigorous species in the study and would likely be successful under future conditions.

Red oak, despite displaying an increasingly negative correlation between growth and spring and summer temperature, showed notable resistance to climatic stressors and was found to have some of the highest average BAI rates of the sampled species. Studies on European oaks as well as native North American oaks (including red oak) in the Mid-Atlantic region and southern United States (Helama et al., 2009; Jenkins & Pallardy, 1995; Leites et al., 2019) find evidence of negative growth responses to urban climates. However, the USDA Climate Change Atlas has also identified red oak as a potentially resilient species from surveys in temperate urban environments similar to that of Toronto (Iverson et al., 2022). As red oak did exhibit a notable increasing negative relationship between growth and temperature in recent decades, it is possible that the current high growth rates of red oak will decrease in the later part of the century, however given that Toronto is in the north of red oak's natural range (Leites et al., 2019) the species may continue to exhibit positive growth trends as the climate becomes more akin to that near its southern range limit.

4.2.2 Species Tolerant to Toronto's Urban Climate

Austrian pine may be less negatively impacted by the urban climate, as the species did not exhibit a negative correlation between growth and summer temperature like the other species, and it also appears to be somewhat drought tolerant. However, the species had comparably low BAI growth compared to other species in the study, which could be due to the species being relatively slow-growing (Manrique-Alba et al., 2021). While Austrian pine at present is not exhibiting severe physiological stress, future change that could include a wetter climate for the region (Lemieux et al., 2005; Wang et al., 2016) would likely cause more stress on the species than what is currently observed, as Austrian pine native range is in warmer and drier Mediterranean regions (Leege & Murphy, 2000; Manrique-Alba et al., 2021).

Sugar maple exhibited a mostly negative correlation between temperature and growth, especially in more recent decades, as well as a declining BAI values since 2010. Despite the species' drought tolerance, sugar maple has been found to be susceptible to negatively impacted by warmer summer temperatures (Hauer et al., 2021; Mulozi et al., 2023; Rudolph & LeBlanc, 2020). The USDA Climate Change Atlas has identified sugar maple as a resilient species; however this study suggests the tree may be more highly stressed in urban environments (Iverson et al., 2022). Thus, as the climate continues to warm, sugar maple may begin to experience greater physiological stress in the city because of higher temperatures, particularly if not offset by increasing precipitation.

4.2.3 Species Poorly Suited for Toronto's Urban Climate

Norway maple, despite being commonly planted in North America for its hardiness and resistance to pollution (Kloeppel & Abrams, 1995; Lazic et al., 2022; Wyckoff & Webb, 1996), did not exhibit strong growth or resistance to climatic stressors. This is in line with a European study which found the species to be susceptible to summer heat (Zimmermann et al., 2015), suggesting the species is not responding well to the stressors of its introduced environment. If the climate continues to change as predicted in the Toronto region (Lemieux et al., 2005; Wang et al., 2016), Norway maple is likely to experience greater stress from both the urban environment and climate change, making its outlook in the region poor. Note that as Norway maple is not native, it was not included in the Climate Change Tree Atlas (Iverson et al., 2022).

4.2.4 Study Limitations and Future Research

This research has filled a gap in current knowledge about the responses of the urban forest to climate in southern Ontario, as a study of this kind has not been regionally undertaken. However, the full scope of the urban environment could not be taken into account as there are a numerous anthropogenic factors not considered that have been demonstrated elsewhere to affect radial tree growth in the city, such

as pollution, road salt, tree trimming, and the restrictions of impermeable surfaces (Dahlhausen et al., 2018; Equiza et al., 2017; Gülten et al., 2016; Mullaney et al., 2015; Ordonez-Barona et al., 2018; Pretzsch et al., 2017; Randrup et al., 2001). In addition, the study was limited as some common tree species in the city, such as blue spruce (*Picea pungens*), Ohio buckeye (*Aesculus glabra*), and tulip poplar (*Liriodendron tulipifera*) were either spatially clustered in few urban locations, were too small to meet the City of Toronto's sampling requirements or were too close to private residences. Several cores were also excluded from the study due to low intercorrelation values or due to poor ring visibility, a common practice in dendrochronological studies (Bartens et al., 2012; Speer, 2010). These results described here are clearly localized to the City of Toronto but may be transferable to other urban areas in southwestern Ontario (Bowery 2023). Studies further afield have found the same species responded to urban environments differently, even in cities that are in similar climates (Cedro & Nowak, 2006; Dahlhausen et al., 2018; David et al., 2018; De Jaegere et al., 2016; Helama et al., 2009). Ideally, urban forest management decisions are best based on local analyses.

Further research could expand on this work by including rural trees of the same species gathered from the city to compare growth trends, particularly as climate change is likely to also impact rural populations. Further research should include measurements of urban pollution and urban heat island effects to further isolate the limiting and enhancing factors of urban tree growth. Additionally, a more complete analysis and comparison of the growth trends of native and non-native species could help to further understand the long-term viability of tree species in southern Ontario.

Hyper-local patterns of urban climate and microclimate could also be evaluated for the impacts on the growth of urban trees. For example, differences in growth of trees growing on north-south vs east-west streets has been evaluated elsewhere (Razzaghmanesh et al., 2021). Further research could also be conducted on the effects of building shade on street tree growth, and the general impacts of sunlight exposure on urban canopies. Air pollution has also been shown to both positively and negatively affect

tree growth (Moser et al., 2016; Moser-Reischl et al., 2019; Pretzsch et al., 2017), a phenomenon that could be further explored in Toronto.

Chapter 5 : Conclusion and Management Recommendations

5.1 Conclusion

This study evaluated the correlations between monthly climate variables (mean monthly temperature and total monthly precipitation) and annual radial growth rates, as well as the average annual basal area increment (BAI) growth rates of five common tree species by growing location in the City of Toronto. Growth rates and climate sensitivity varied by both species and growing location. Norway maple and sugar maple growth was negatively correlated with summer temperature, a relationship which has increased in strength recently, in line with both species displaying a negative growth trend in the BAI analysis. Linden and Austrian pine have not displayed a response to summer temperatures, with Austrian pine also not displaying a response to precipitation. Red oak demonstrated a positive response to precipitation, but also an increasing sensitivity to summer temperatures, yet a high BAI growth rate.

This research has filled a gap in current knowledge about the responses of the urban forest to climate in southern Ontario, as a study of this kind has not been regionally undertaken. These results described here are clearly localized to the City of Toronto, but may be transferable to other urban areas in southwestern Ontario (Bowery 2023). Studies further afield have found the same species responded to urban environments differently, even in cities that are in similar climates (Cedro & Nowak, 2006; Dahlhausen et al., 2018; David et al., 2018; De Jaegere et al., 2016; Helama et al., 2009). Ideally, urban forest management decisions are best based on local analyses.

5.2 Management Recommendations

5.2.1 Management Recommendations – Other Suitable Species

While not included in the study, the following species are also considered well suited to the urban environment and have been shown to be resistant to many of the effects of climate change (Iverson et al., 2019). White oak (*Quercus alba*) has a large natural geographic range in North America that, similar to red oak, displays high tolerance to the urban environment as well as tolerance to a wide range of temperatures (Iverson et al., 2019). The species currently grows naturally in Ontario and as the climate continues to warm the Toronto region is expected to become more hospitable to the species (Iverson et al., 2019). Honey locust (*Gleditsia triacanthos*) is not as widely distributed as white oak yet has also been shown to be resistant to the changing climate, with modelled ranges showing the species would be well adapted to a warmer Toronto (Iverson et al., 2019). Honey locust is already common in the city but was not sampled due to insufficient accessible specimens but would be useful to evaluate locally in the future. Black gum (*Nyssa sylvatica*) is widely distributed across the southern and mid-Atlantic United States, with only extreme southern Ontario currently in its native range. However, warming temperatures and current climate change modelling projects that the species will migrate north, with the Toronto region likely having a suitable future climate for the species, making it a potential planting candidate (Iverson et al., 2019). Bitternut hickory (*Carya cordiformis*) is currently distributed across much of the mid-Atlantic United States, Great Lakes region, and southern Ontario. The species displays strong drought tolerance, as well as an expected range shift north into Ontario (Iverson et al., 2019), making the species suitable for planting in parks and especially streets in Toronto.

5.2.2 Planting Recommendations – Sampled Species

Two of the sampled species are good candidates for future planting in Toronto, red oak and sugar maple. Red oak displayed notable resistance to climactic stressors and displayed strong BAI growth rates over the sample period. Red oak occurs naturally in the region and provides key ecosystem services and habitat for local species (Tian et al., 2022), and thus is a suitable candidate for continued planting in the city. Although sugar maple displayed increased stress and reduced growth rates in recent decades, it is also recommended for planting as it too occurs naturally in the region and, like red oak, can provide key ecosystem services (Rudolph & LeBlanc, 2020). However, as it displayed elevated stress to summer temperatures it is not recommended as a street tree due to the impact of impermeable surfaces on growth and water penetration (North et al., 2017; Randrup et al., 2001), making it advisable to plant it in park-like environments.

The other sampled species, linden, Norway maple, and Austrian pine are not advisable for continued planting in the city. Despite exhibiting resistance to the urban environment, and displaying strong growth over the sample period, linden is not recommended for planting. As linden is a non-native species it risks further expanding into natural environments and competing with native species (Liebhold et al., 1995; Martynova et al., 2020; Wyckoff & Webb, 1996). Norway maple displayed notable sensitivities to climate, with a strong negative association between summer temperature and growth, which coincided with comparably low BAI growth rates. Also, Norway maple is an introduced species, thus runs the risk of competing with native tree species and spreading into natural environments (Liebhold et al., 1995; Martynova et al., 2020; Wyckoff & Webb, 1996). Austrian pine exhibited resilience to the urban climate, yet

displayed low BAI growth rates, and is similarly not recommended for planting due to it also being an introduced non-native species.

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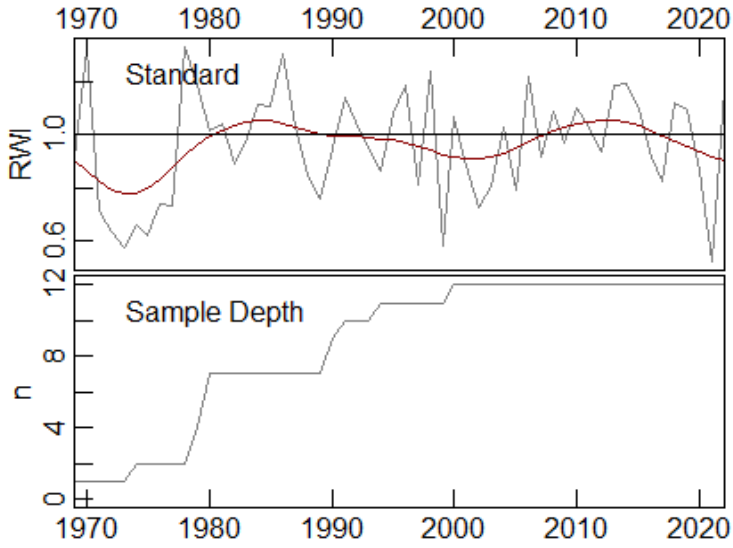
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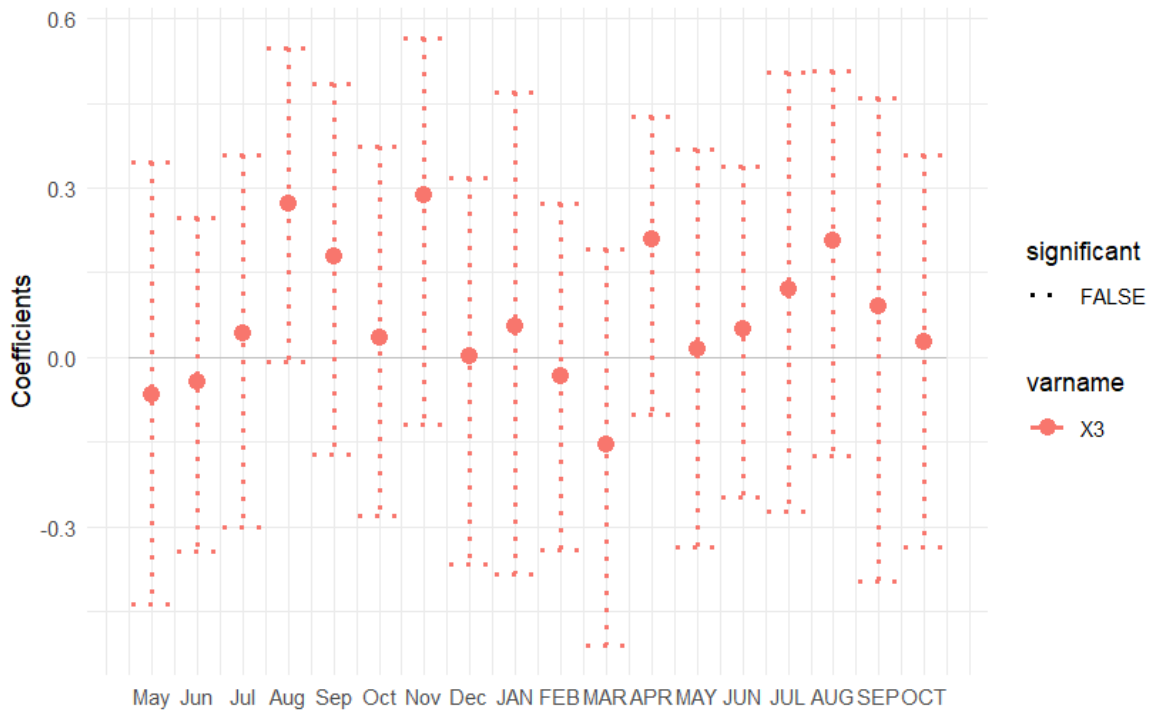
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Appendix



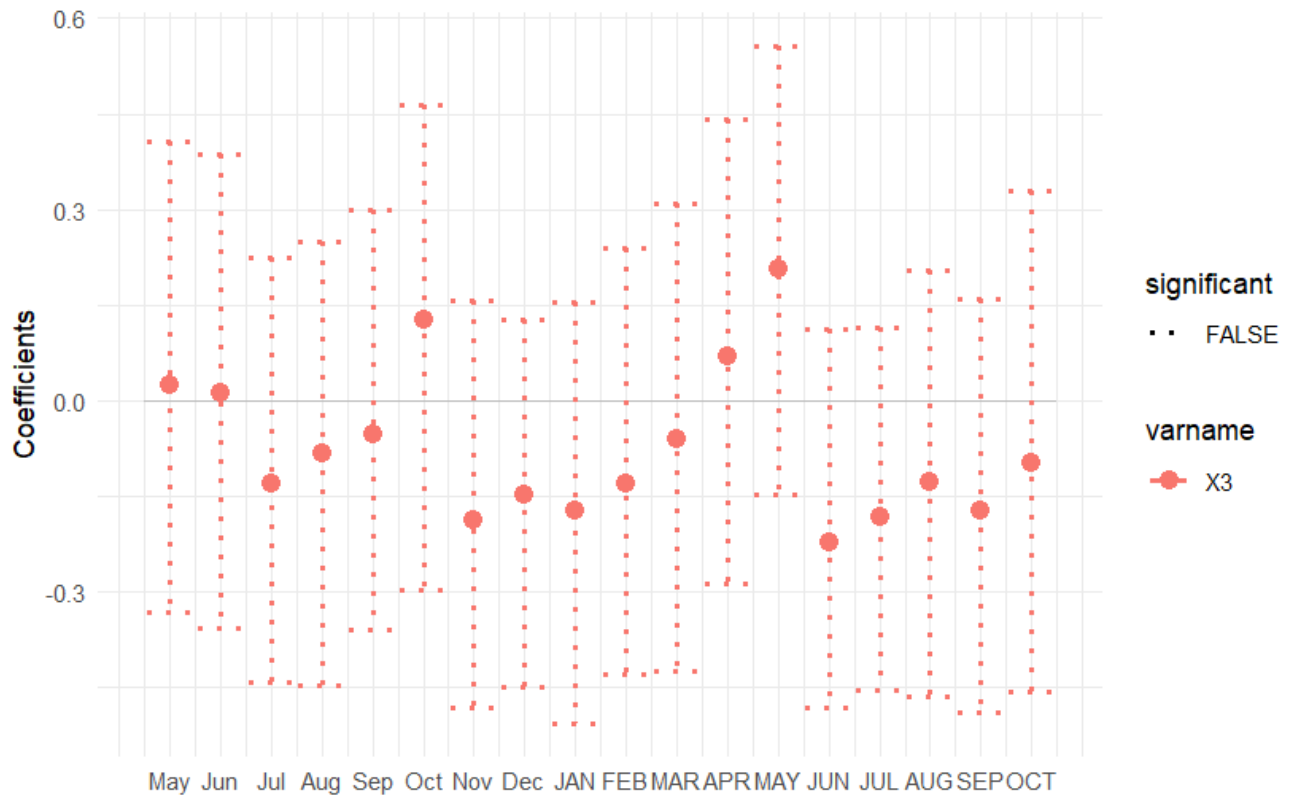
Appendix Figure 1: RWI (Ring Width Index) and sample depth for park linden

Red line is cubic smoothing spline fitted to RWI.



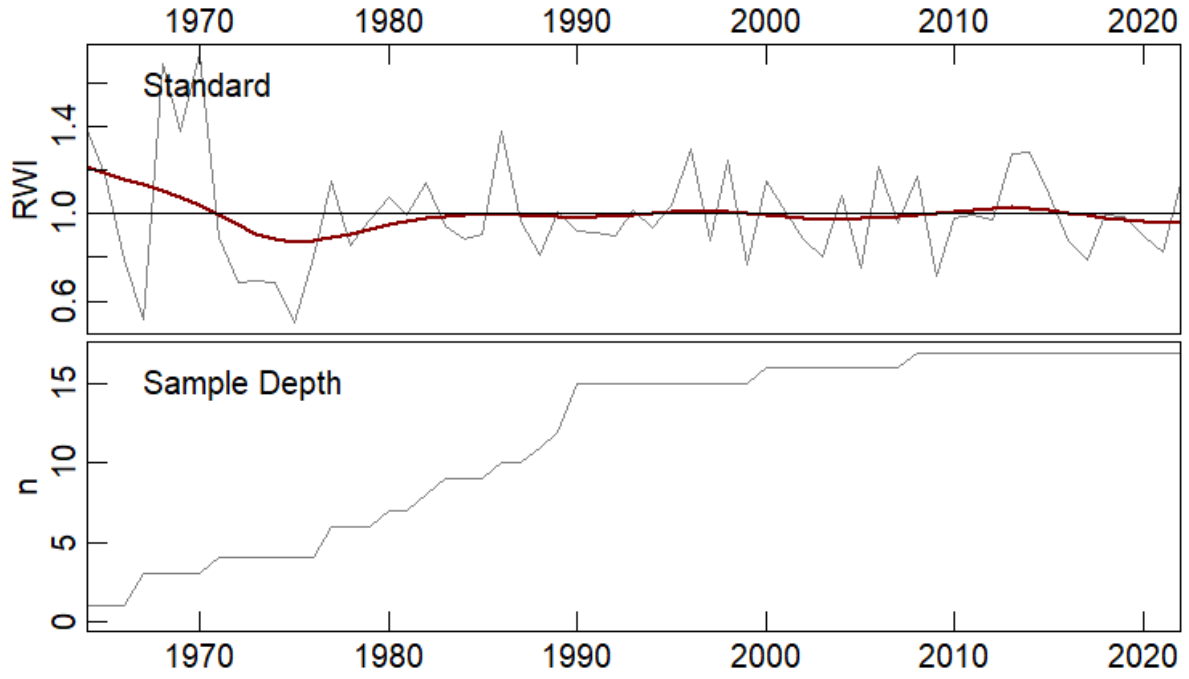
Appendix Figure 2: Precipitation static correlation plot for park linden.

Solid line represents a significant correlation, confidence intervals are represented by lines.



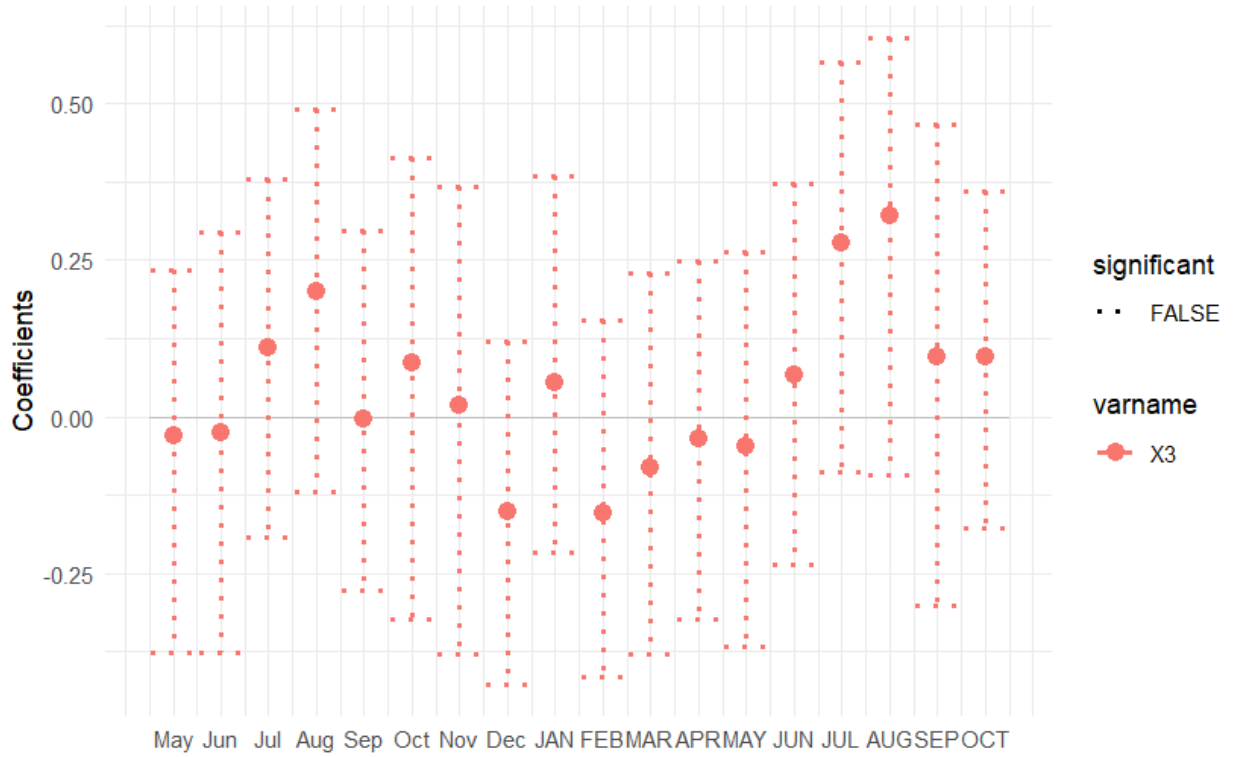
Appendix Figure 3: Temperature static correlation plot for park linden.

Solid line represents a significant correlation, confidence intervals are represented by lines.



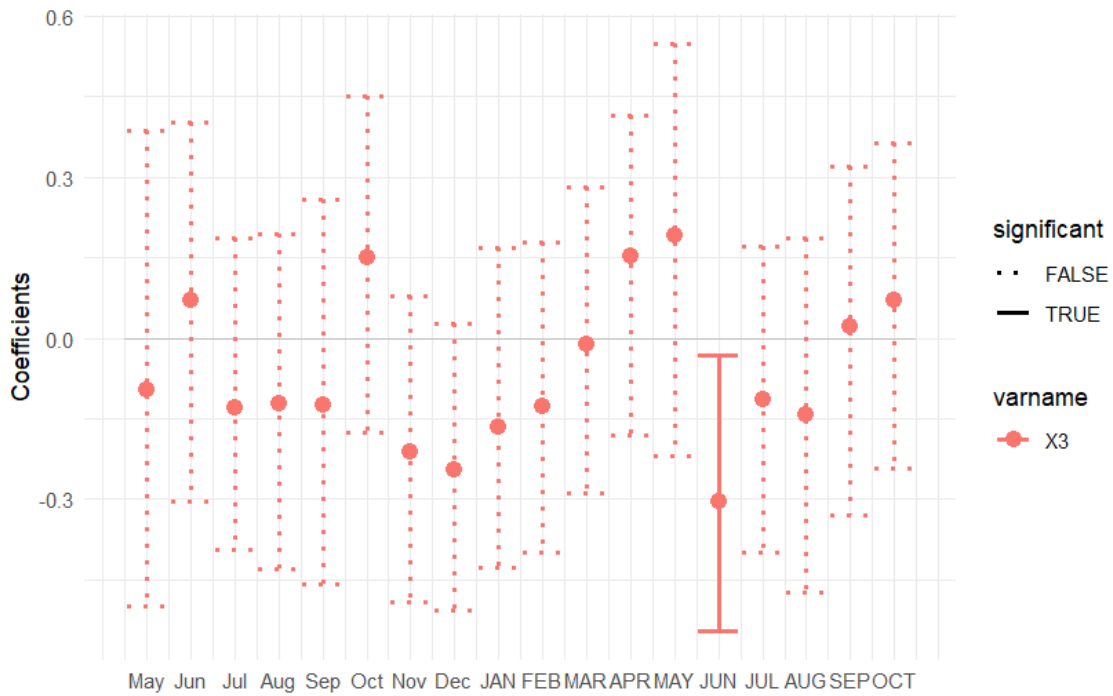
Appendix Figure 4: RWI and sample depth for street linden.

Red line is cubic smoothing spline fitted to RWI.



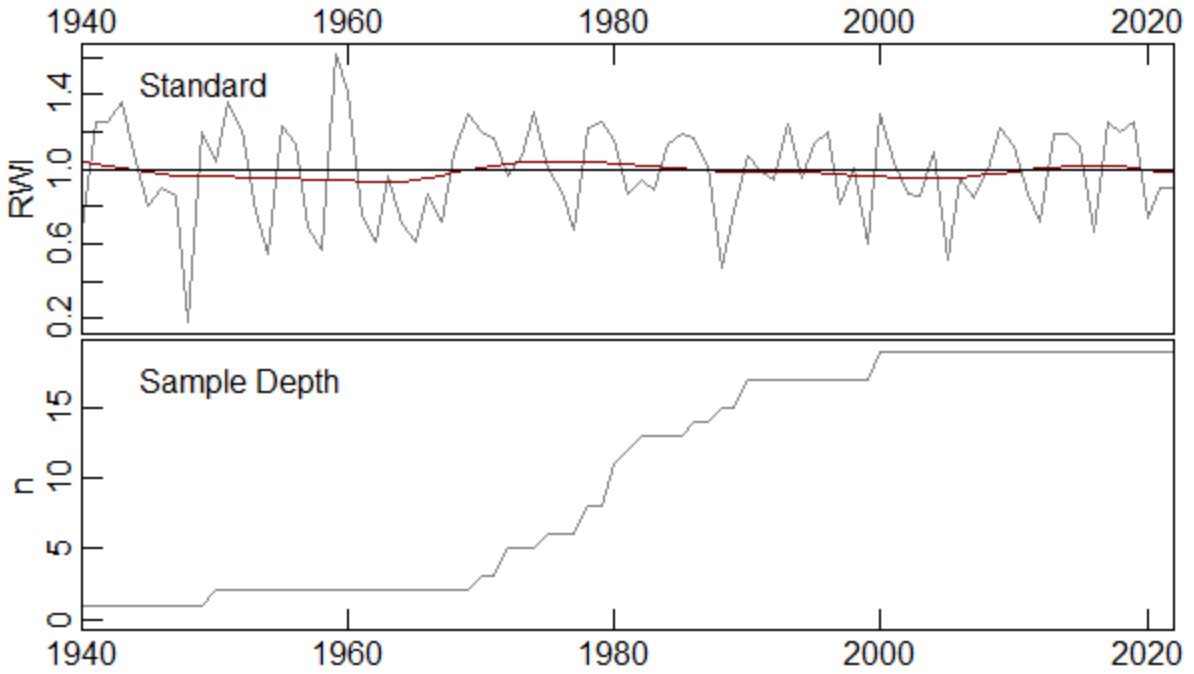
Appendix Figure 5: Precipitation static correlation plot for street linden.

Solid line represents a significant correlation, confidence intervals are represented by lines.



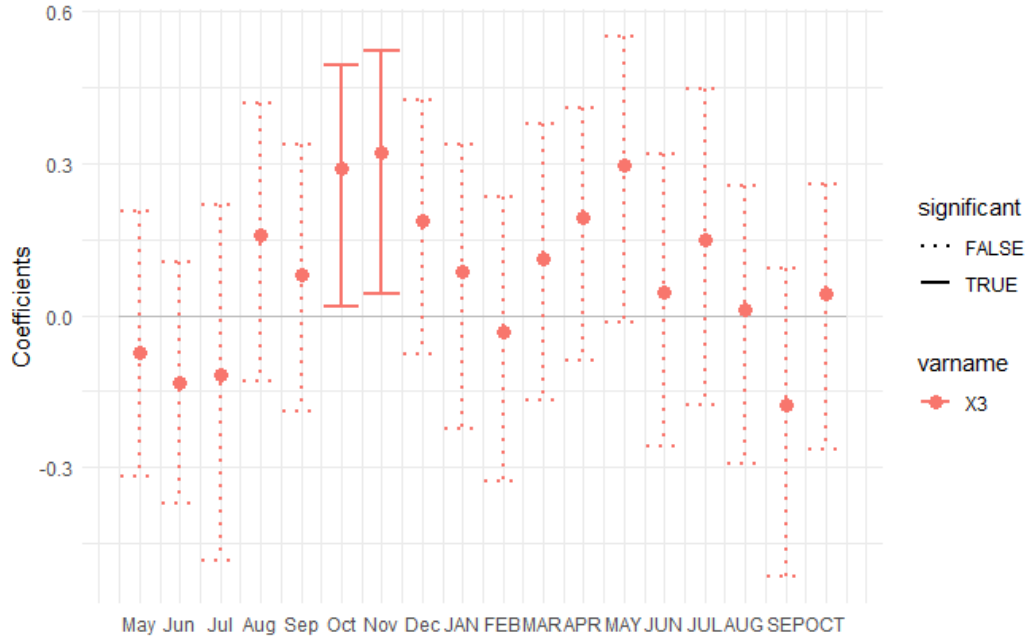
Appendix Figure 6: Temperature static correlation plot for street linden.

Solid line represents a significant correlation, confidence intervals are represented by lines.



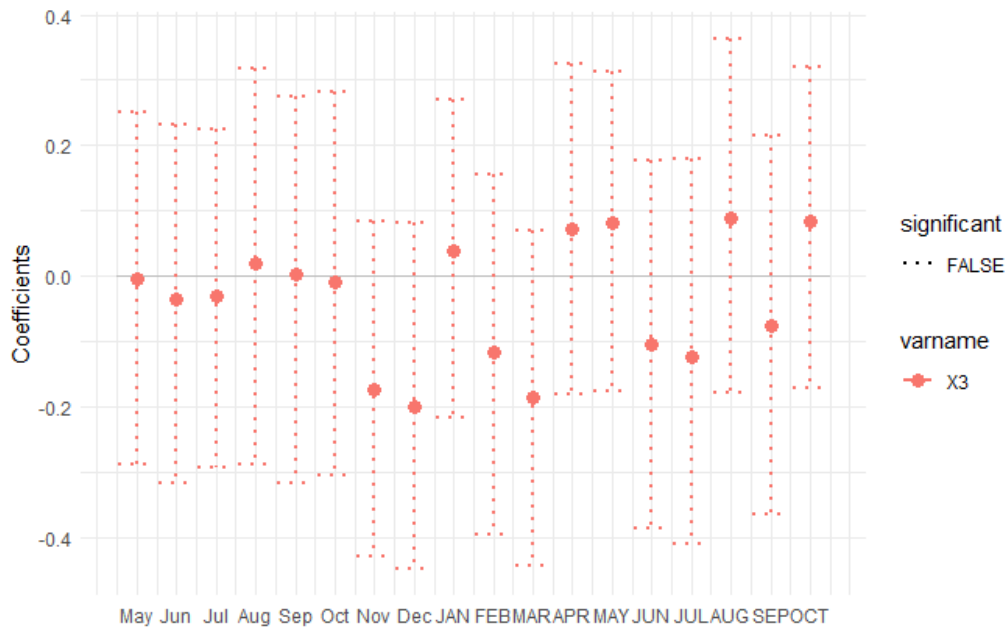
Appendix Figure 7: RWI and sample depth for park Norway maple.

Red line is cubic smoothing spline fitted to RWI.



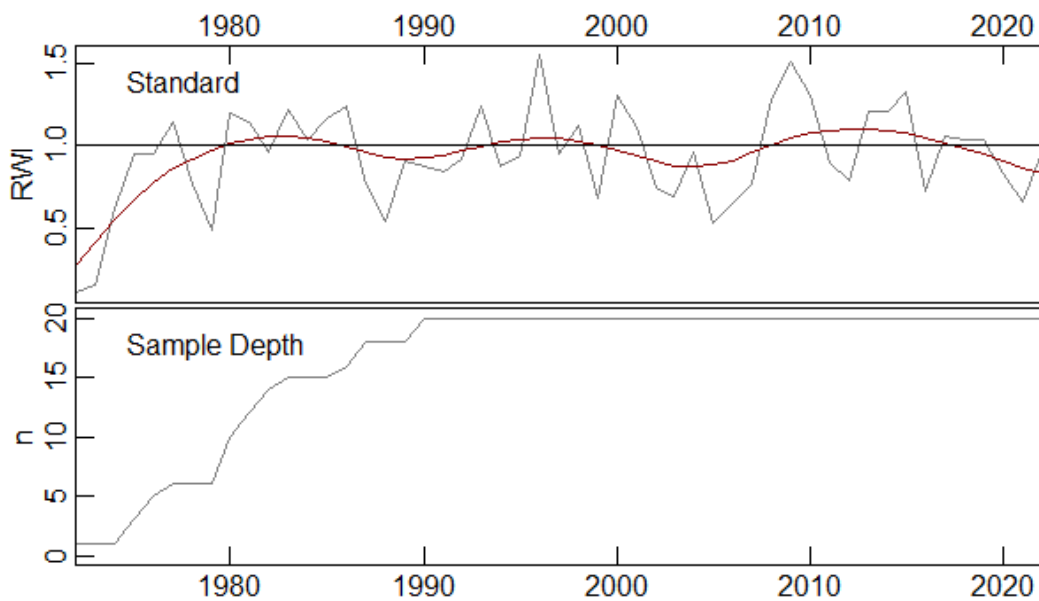
Appendix Figure 8: Precipitation static correlation plot for park Norway maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



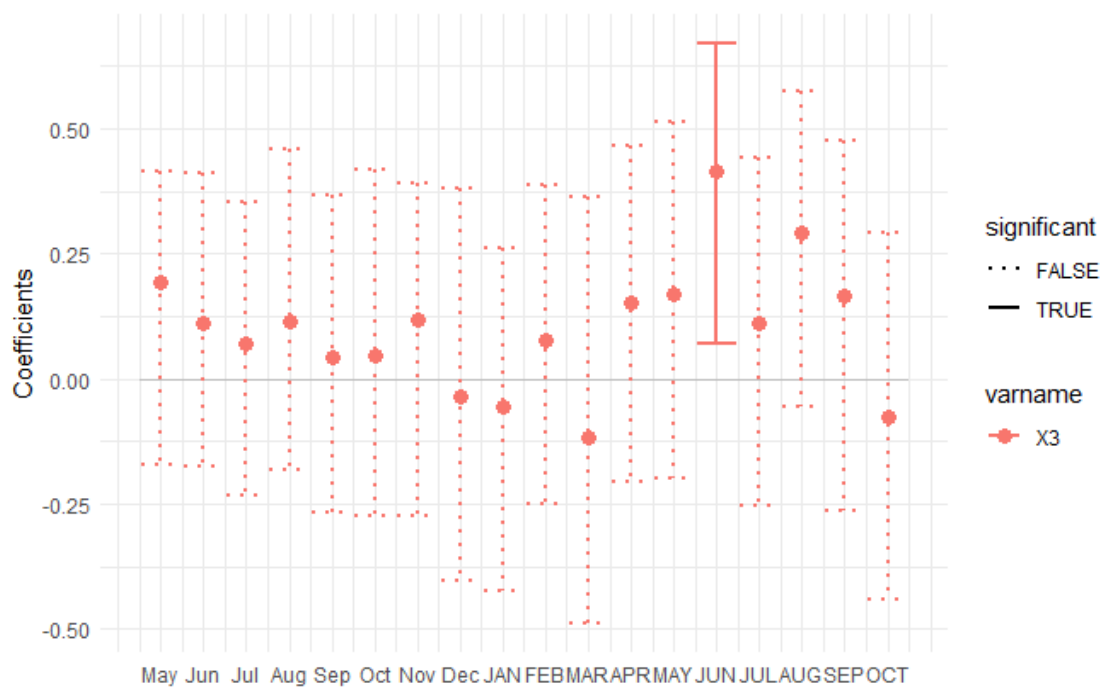
Appendix Figure 9: Temperature static correlation plot for park Norway maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



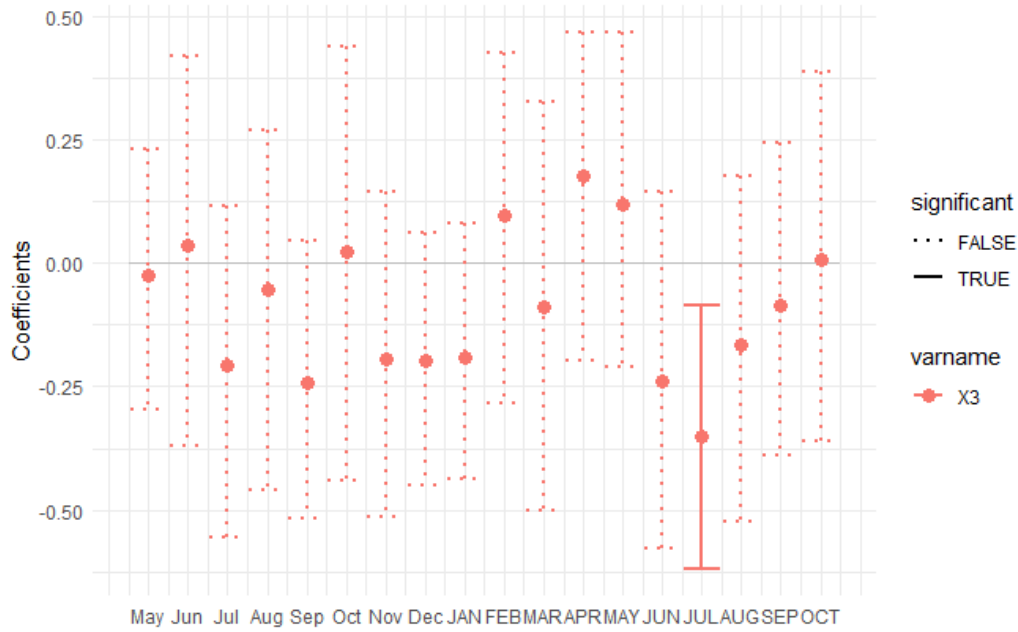
Appendix Figure 10: RWI and sample depth for street Norway maple.

Red line is cubic smoothing spline fitted to RWI.



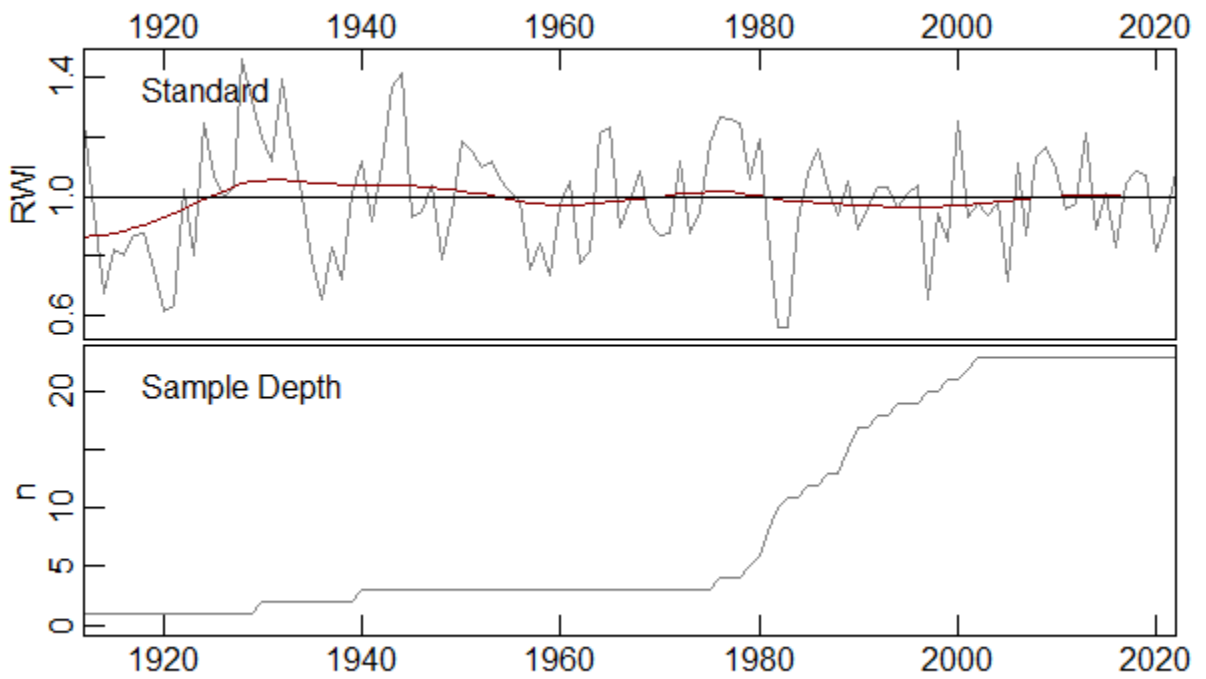
Appendix Figure 11: Precipitation static correlation plot for street Norway maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



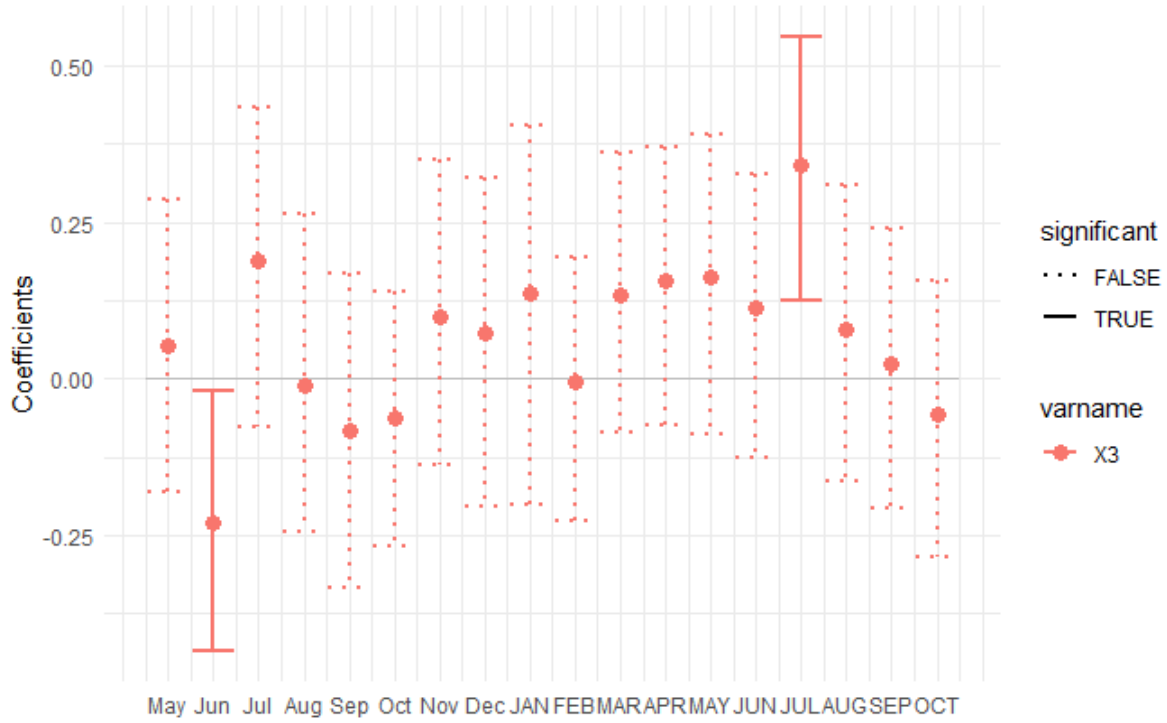
Appendix Figure 12: Temperature static correlation plot for street Norway maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



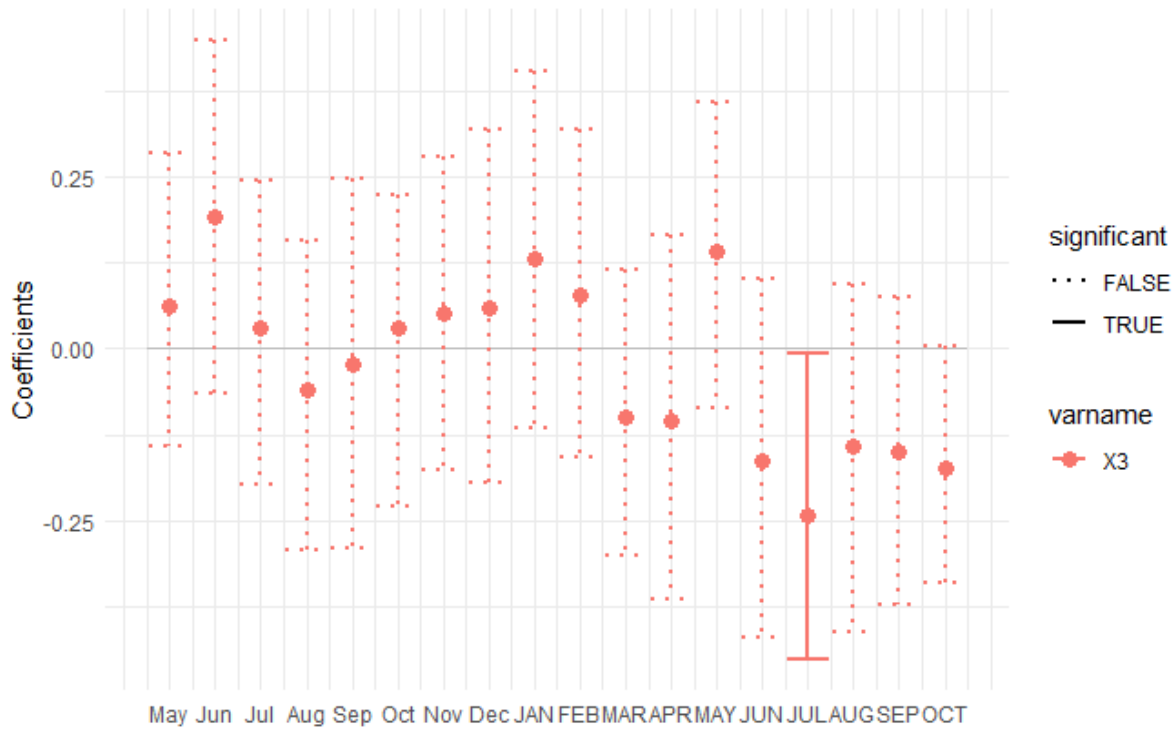
Appendix Figure 13: RWI and sample depth for park red oak.

Red line is cubic smoothing spline fitted to RWI.



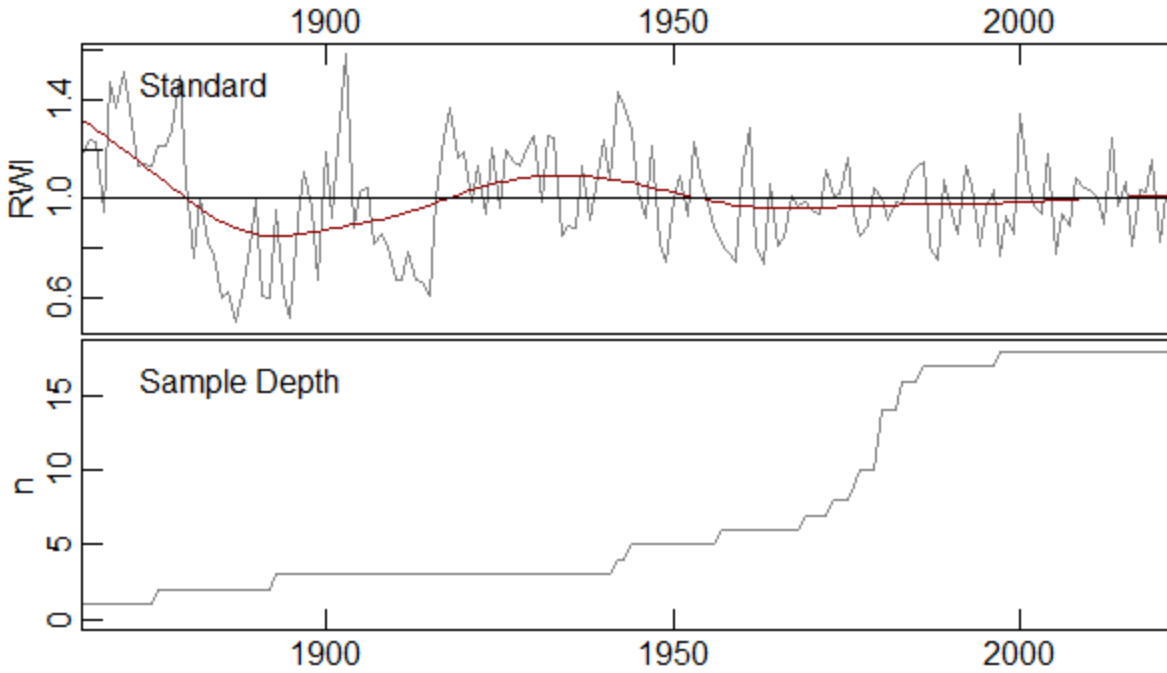
Appendix Figure 14: Precipitation static correlation plot for park red oak.

Solid line represents a significant correlation, confidence intervals are represented by lines.



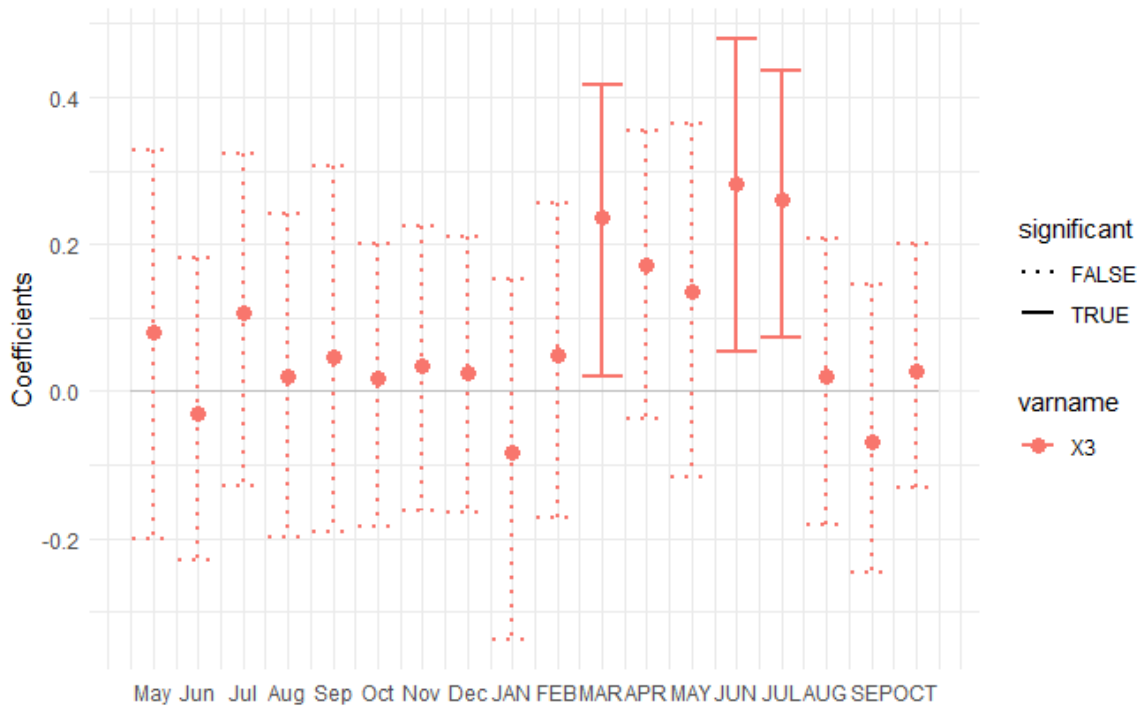
Appendix Figure 15: Temperature static correlation plot for park red oak.

Solid line represents a significant correlation, confidence intervals are represented by lines.



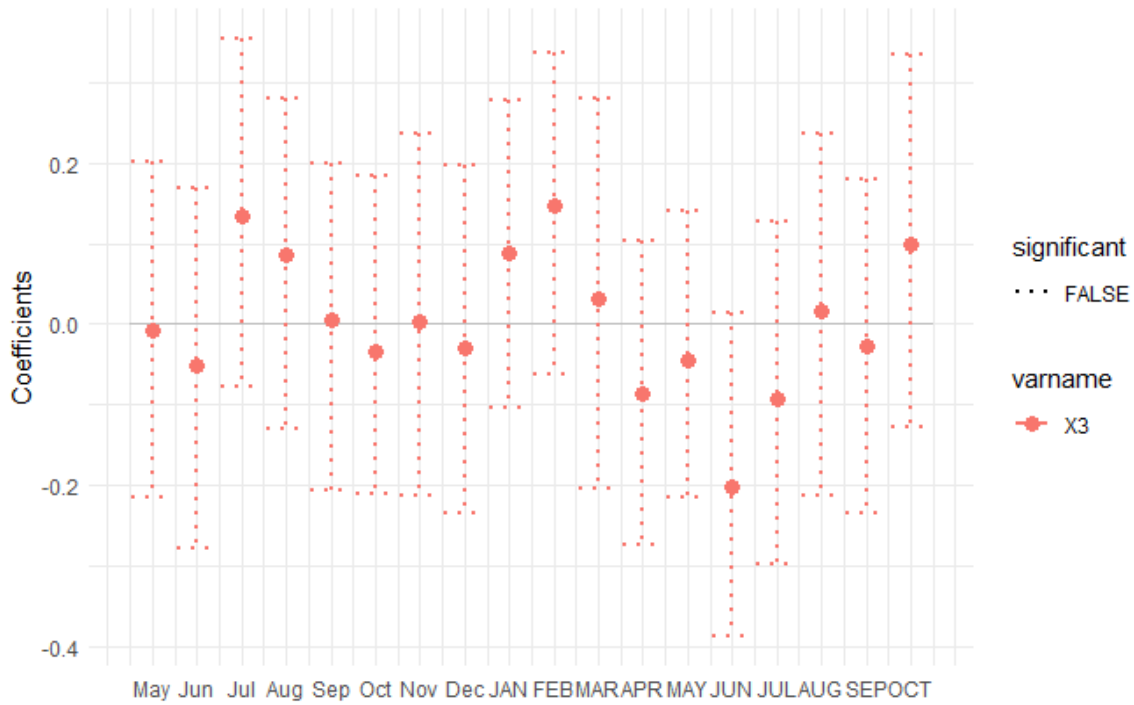
Appendix Figure 16: RWI and sample depth for street red oak.

Red line is cubic smoothing spline fitted to RWI.



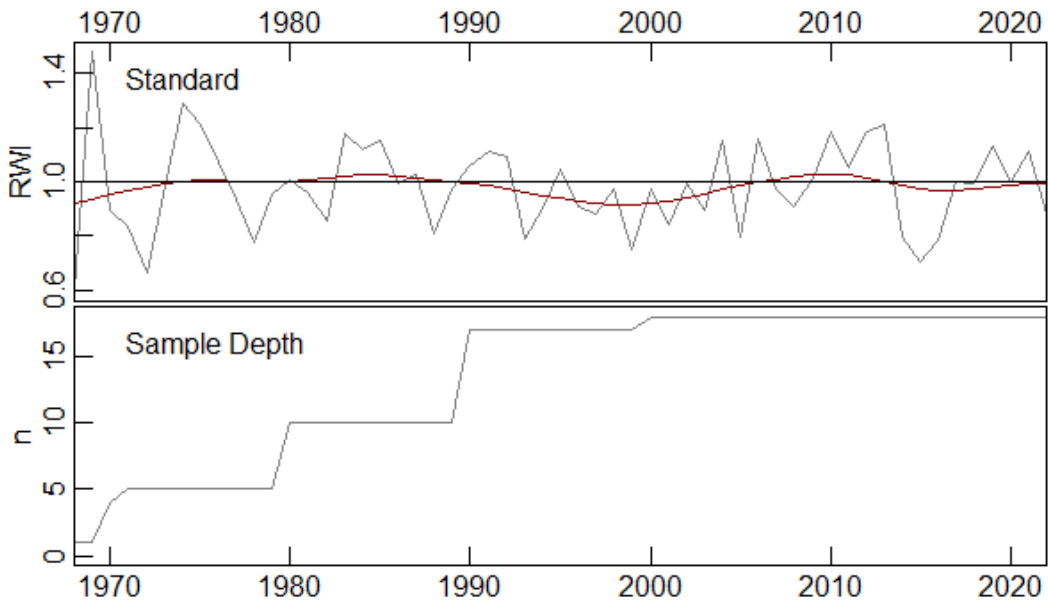
Appendix Figure 17: Precipitation static plot for street red oak.

Solid line represents a significant correlation, confidence intervals are represented by lines.



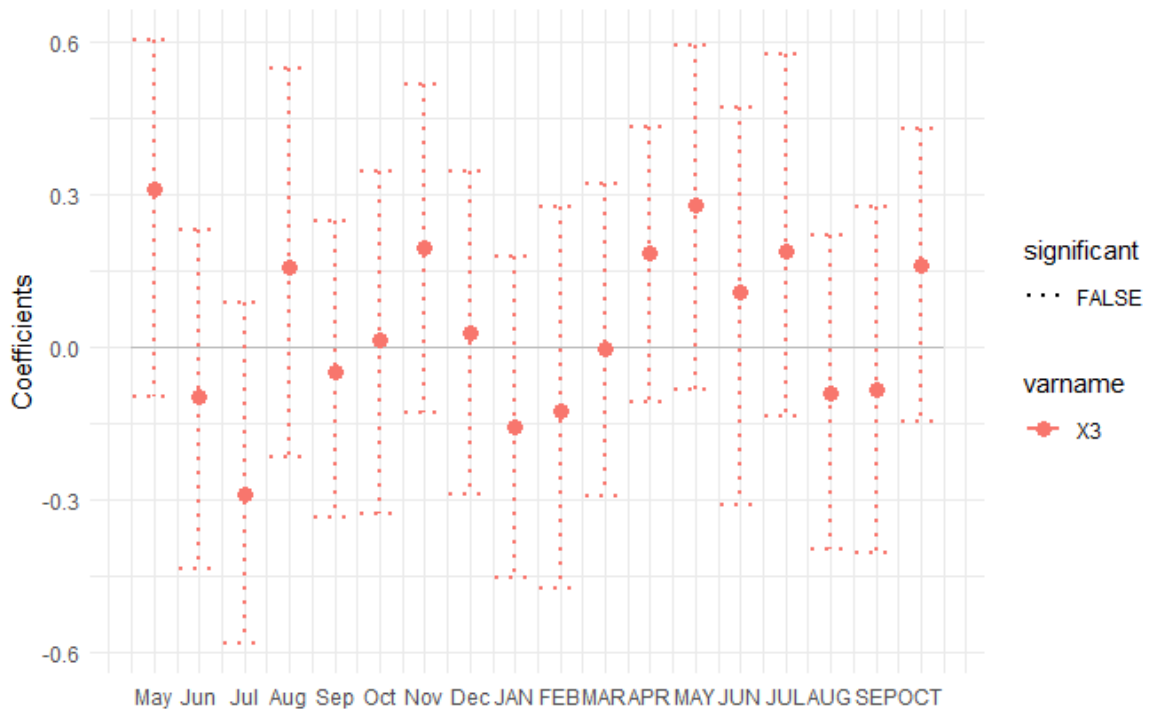
Appendix Figure 18: Temperature static plot for street red oak.

Solid line represents a significant correlation, confidence intervals are represented by lines.



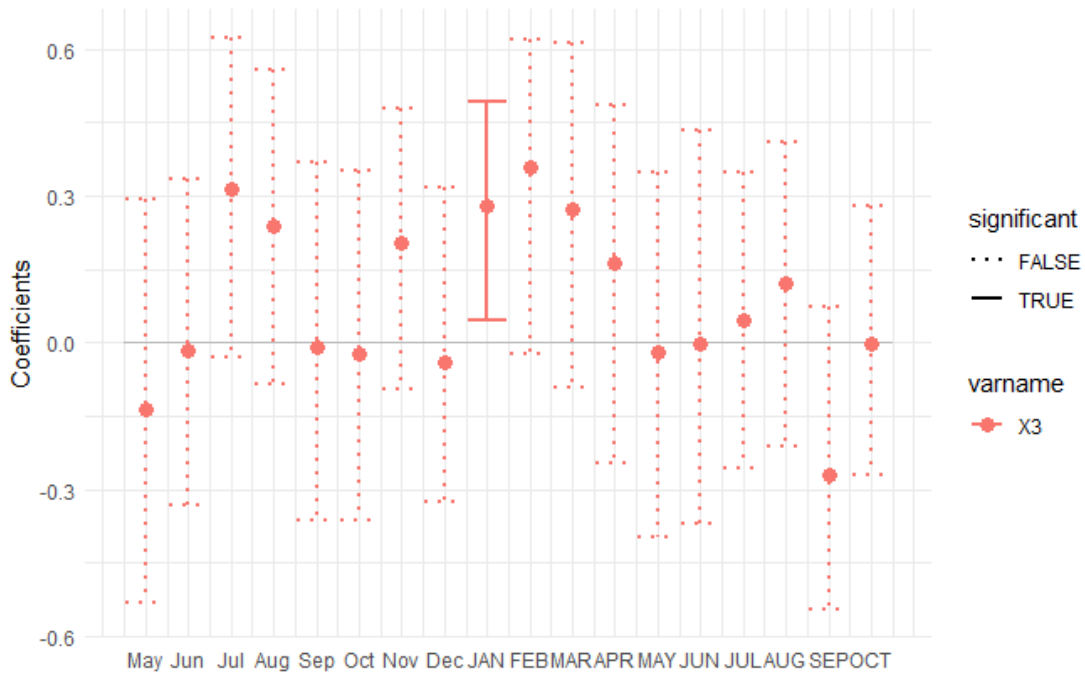
Appendix Figure 19: RWI and sample depth for park Austrian pine.

Red line is cubic smoothing spline fitted to RWI.



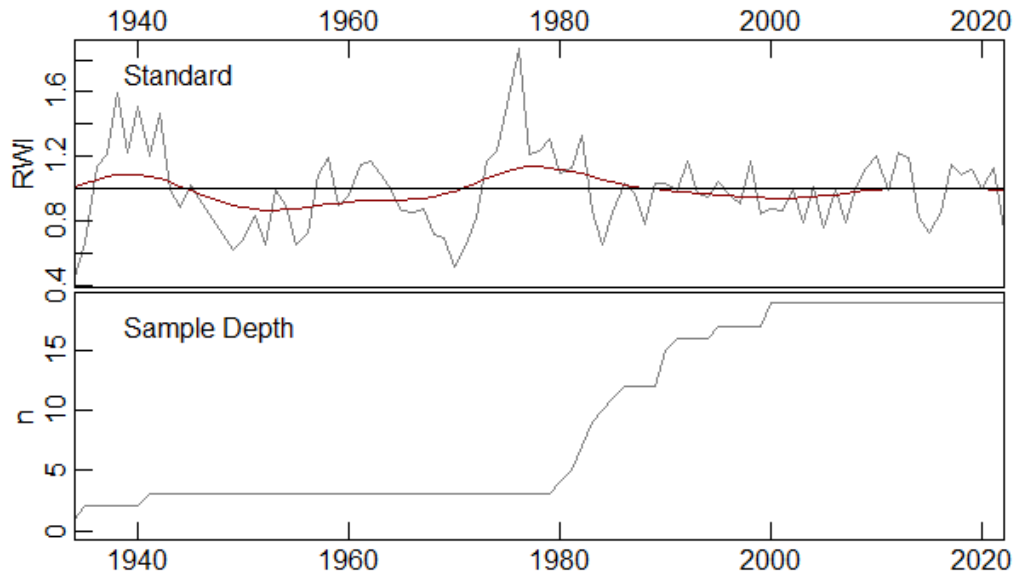
Appendix Figure 20: Precipitation static correlation plot for park Austrian pine.

Solid line represents a significant correlation, confidence intervals are represented by lines.



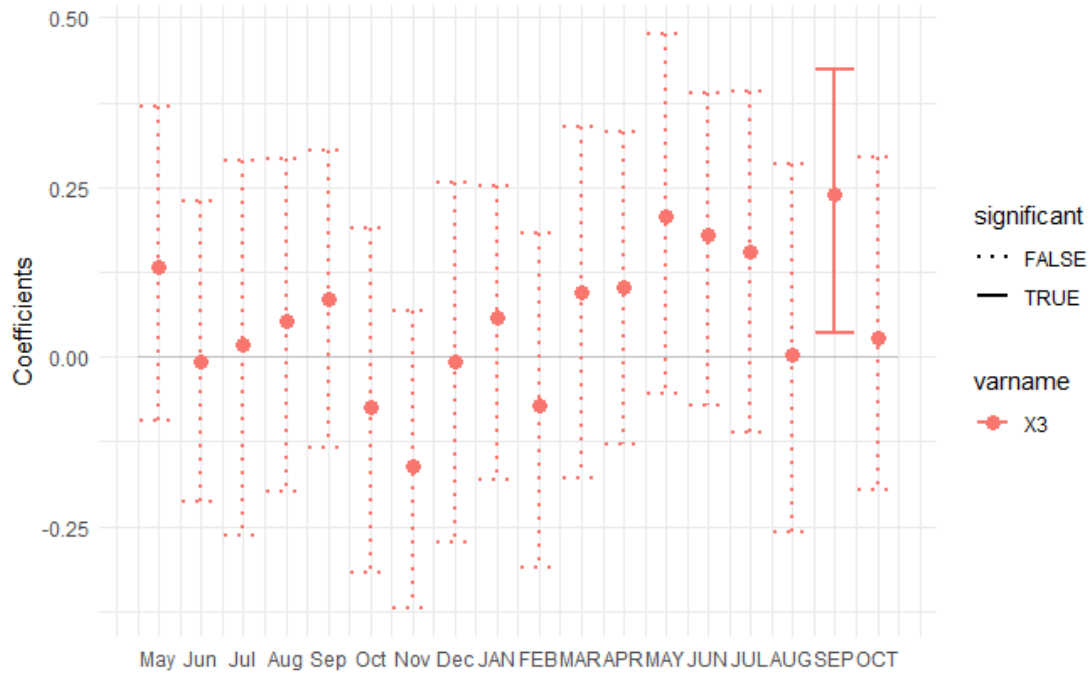
Appendix Figure 21: Temperature static correlation plot for park Austrian pine.

Solid line represents a significant correlation, confidence intervals are represented by lines.



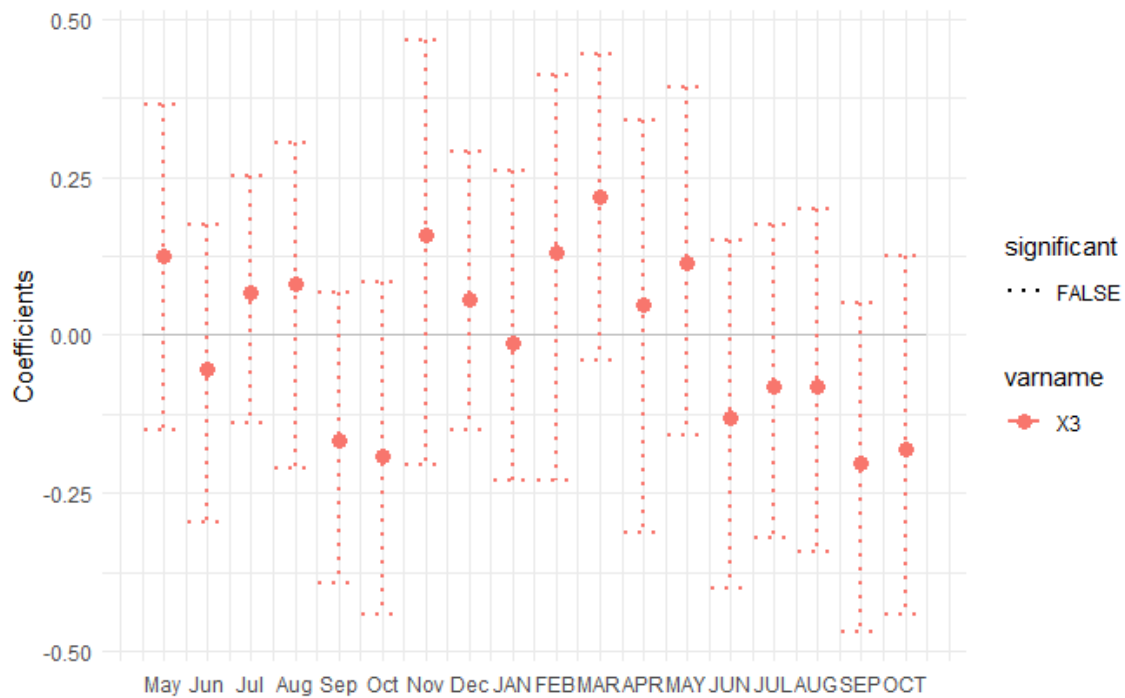
Appendix Figure 22: RWI and sample depth for street Austrian pine.

Red line is cubic smoothing spline fitted to RWI.



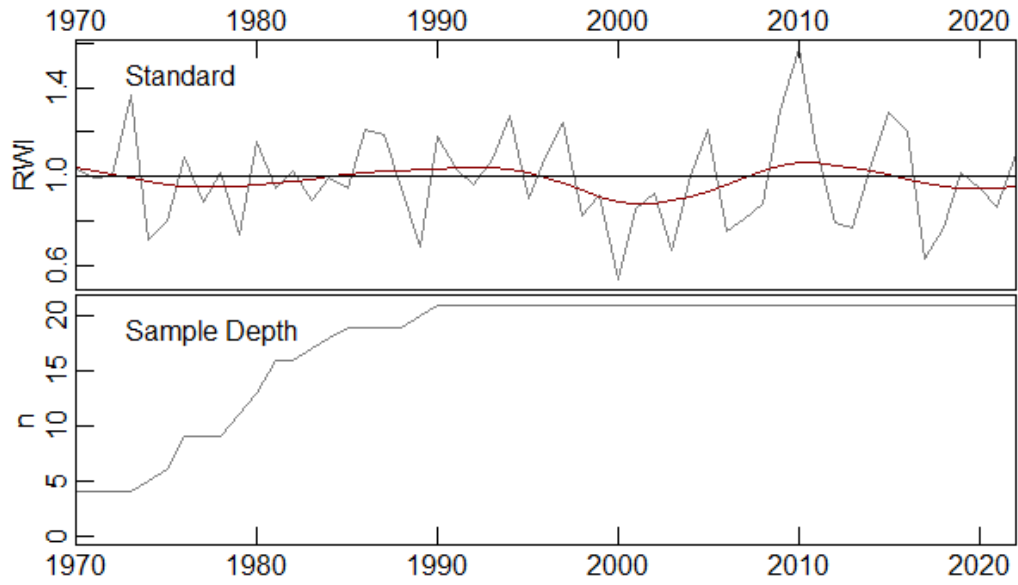
Appendix Figure 23: Precipitation static correlation plot for street Austrian pine.

Solid line represents a significant correlation, confidence intervals are represented by lines.



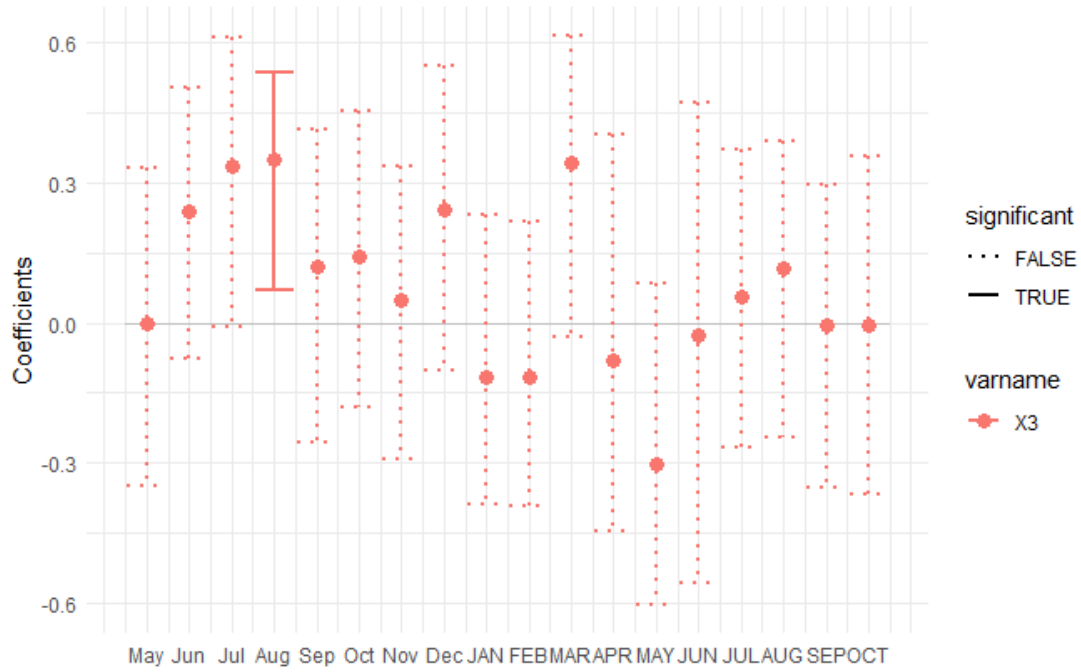
Appendix Figure 24: Temperature static correlation plot for street Austrian pine.

Solid line represents a significant correlation, confidence intervals are represented by lines.



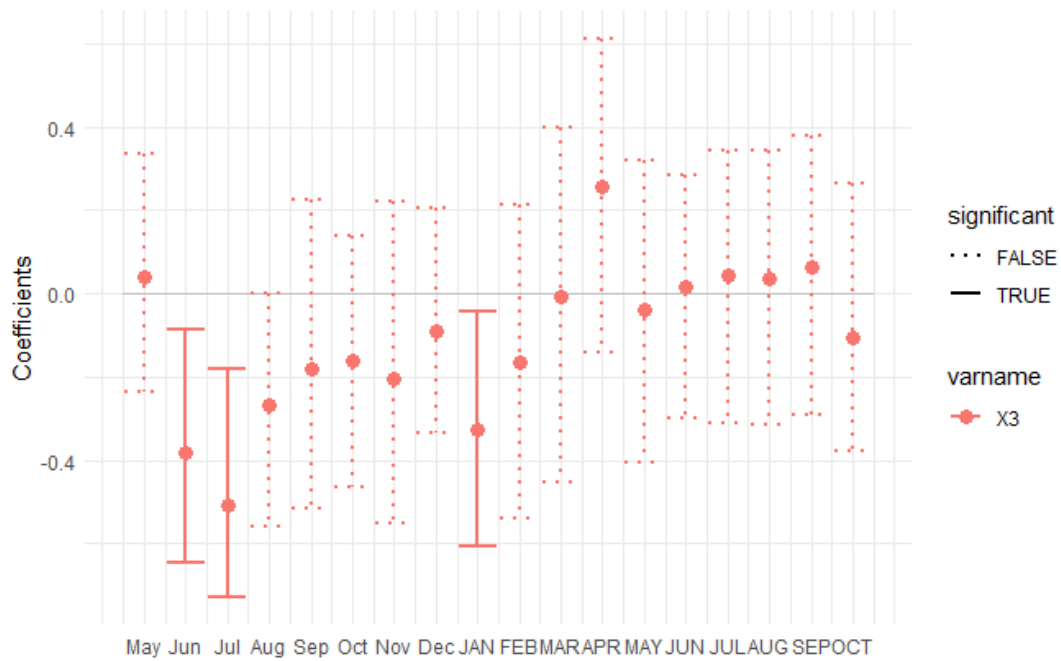
Appendix Figure 25: RWI and sample depth for park sugar maple.

Red line is cubic smoothing spline fitted to RWI.



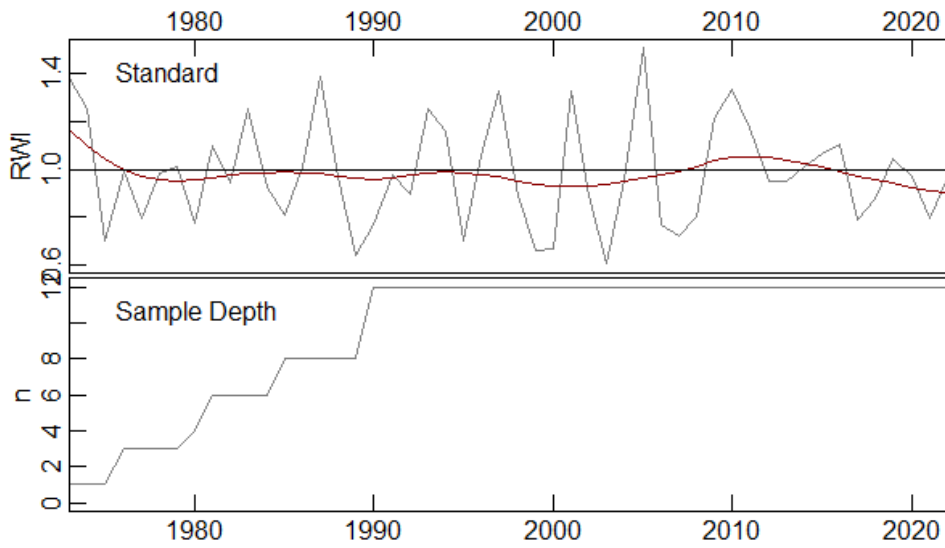
Appendix Figure 26: Precipitation static correlation plot for park sugar maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



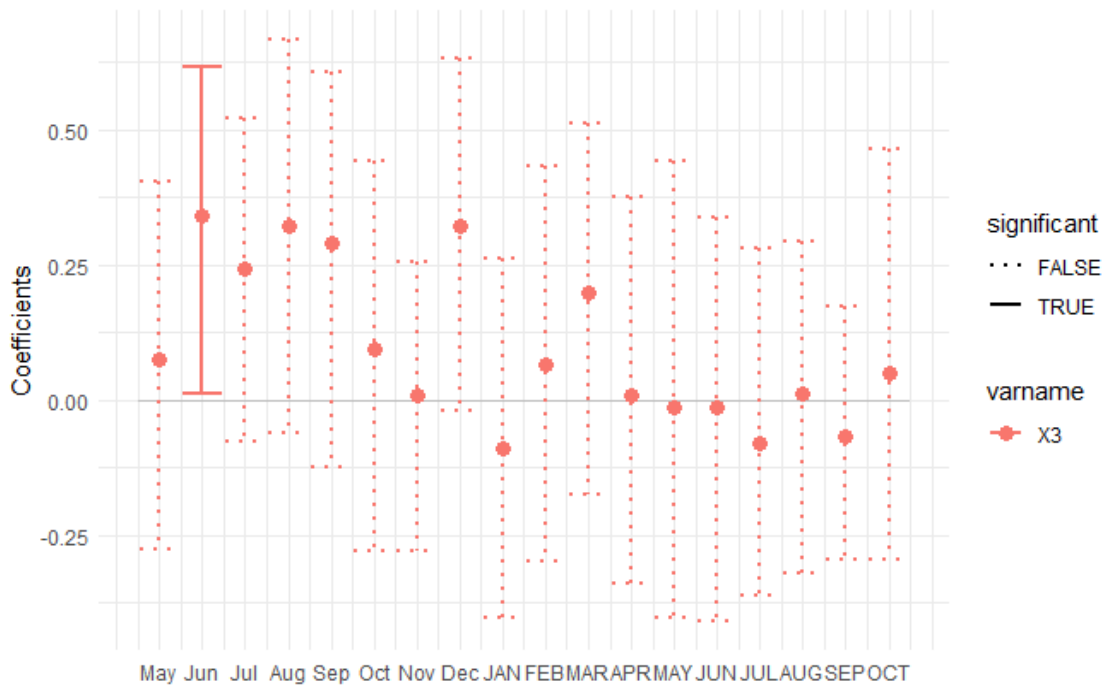
Appendix Figure 27: Temperature static correlation plot for park sugar maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



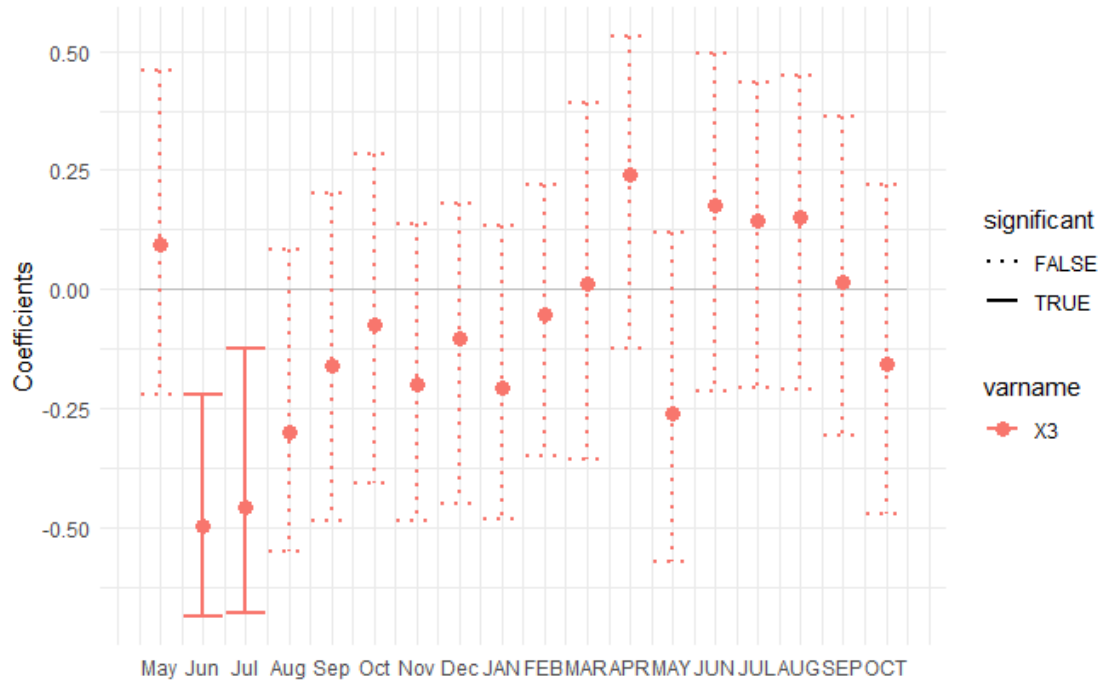
Appendix Figure 28: RWI and sample depth for street sugar maple.

Red line is cubic smoothing spline fitted to RWI.



Appendix Figure 29: Precipitation static correlation plot for street sugar maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.



Appendix Figure 30: Temperature static correlation plot for street sugar maple.

Solid line represents a significant correlation, confidence intervals are represented by lines.