Assessing the growth and survival of the Alice Holt coast redwood provenance trial using dendrochronology and climate data

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1 Executive Summary

As forests and woodlands continue to be affected by the changing climate, they will undoubtedly experience a change in the risks that they face. Therefore, choosing the appropriate tree species and provenances for the future local climate and site characteristics of a stand are key management decisions that need to be made. Coast redwood is a novel, evergreen conifer that is currently classed as a secondary species in the UK and highlighted as an emerging species for British forestry due to the positive silvicultural characteristics that it demonstrates.

While there is limited published research specifically assessing the performance of coast redwood in the UK, the species is nonetheless reasonably well understood and has demonstrated promising traits under current conditions, supporting its potential for wider use. As coast redwood is regarded as not being drought tolerant and vulnerable to late spring frosts, especially while young, it is important to understand the challenges this species may face in the UK with a changing climate with longer, more severe droughts and increasing risk of late spring frosts due to advances in plant spring bud-burst.

We piloted a study examining the survival and climate response of a 20th century coast redwood provenance trial in SE England through dendrochronological sampling. For this we collected 46 tree-core samples from 5 different provenances and used historical records of survival and climate data for our analysis. Our results showed that the ring width index (RWI) displayed some inter-annual variability; with reductions in tree ring growth corresponding to periods of documented drought in the UK. These findings suggest that coast redwood is sensitive to drought conditions, with annual RWI values declining by approximately 15–50% during severe and extreme drought years. Stand survival data showed that once trees reached seven years of age, their likelihood of survival increased markedly, indicating a critical threshold for successful establishment (Jinks & Kerr, 2016). We attempted to link changing survival rates with late spring frost events, but further

research is needed to determine the timing of the onset of growth in coast redwood in UK conditions, as this information is critical for assessing the species' vulnerability to late spring frost events and their potential impact on early survival.

Our findings will be useful in the assessment of novel species, coastal redwood provenance choice and the challenges associated with frost events and their effect on choosing and introducing novel species, but we note that more evidence will be required from other replicated trials to reinforce our findings. Additionally, we emphasize the need for a deeper understanding of the phenological patterns and seasonal growth dynamics of novel species, particularly the timing and variability of bud burst, as well as their resistance, resilience, and recovery to drought. These factors are critical in shaping growth performance and determining vulnerability to climatic stressors under future environmental conditions.

2 Introduction

2.1 Coast redwood

Coast redwood (*Sequoia sempervirens*) (RSQ) is an evergreen conifer, native to a narrow coastal strip of the West Coast of the United States, stretching from southern Oregon to south of Monterey in California. Coast redwood is the world's tallest tree and shows rapid early growth, being able to achieve 45m in height by 50 years in its native habitat, and under optimal conditions, it can exceed 110 meters in height and live for more than 2,000 years (Wilson et al., 2016). Coast redwood was first introduced into Britain in 1843 and was often planted as a single or group of specimens that are frequently found in formal gardens, estates and parks, but has also been trialled on a limited scale to test different provenances from its north-south range in contrasting conditions in southern England. In its native range, coast redwood grows best in a mild, humid climate with frequent fogs, average temperatures of 10-16°C, and annual precipitation ranging from 640mm to 3100mm (Wilson et al., 2016). For UK conditions, Forest Research (2025) outlines that coast redwood is best suited to grow on poor to medium soils of ‘fresh’ or ‘moist’ soil moisture categories in Wales and south-east England where rainfall exceeds 1250mm.

In response to the increasing threats to tree species in the UK with a changing climate, several alternative species are being considered to widen the palette of tree species and support efforts to adapt British forests, including coast redwood (Reynolds et al., 2021). Although coast redwood is intolerant to wind and salt exposure, not considered drought tolerant due to its high-water usage and is vulnerable to late spring frosts when young, its shade tolerance and rapid early growth make it an ideal species for underplanting on existing forest land (Forest Research, 2016). In native California, coast redwood exhibits notable resilience due to its resistance to wildfire and decay, and the absence of any major insect pests or diseases of concern. The fire resistance of coast redwood in its native habitat is attributed to the tree’s unique bark and its chemical composition. The bark is thick (up to 30cm) and fibrous, offering excellent insulation and heat dispersal throughout its layers. The presence of the natural flame retardant and decay-resistant chemical tannin which gives the bark and heart wood it’s reddish colour, and the minimal production of flammable resin also contribute to its fire resistance (Carroll et al., 2018; Madej, 2010; Tributsch & Fiechter, 2008).

The Future Productive Species for Scotland report highlights that RSQ is currently a secondary species within the UK forestry sector and has been included in the final shortlist of 28 productive species for Scotland (Edwards et al., 2025). In contrast, RSQ is featured as the top species in the Top Five Alternative Conifer Tree Species in Great Britain report (Peters et al., 2021). Outlined as an “emerging species”, coast redwood is reasonably well understood, and it has demonstrated its suitability for forestry under current conditions and so has potential for wider use in future (Reynolds et al., 2021).

Under a changing climate, the risks associated with drought and frost are shifting — droughts are expected to become more frequent and severe, while frosts may become less frequent but still pose a threat, particularly to young trees (Ray et al., 2025). To understand coast redwood's sensitivity to these evolving risks, historical records of survival and analyses of Ring Width Index (RWI) are being used to assess how growth and survival have responded to past climatic stressors. These approaches help reveal patterns of decline and resilience, offering valuable insights into the species' potential performance under future UK conditions.

2.2 Provenance trials

2.2.1 Alice Holt provenance trial

The coast redwood provenance trial (AH 147) is in Alice Holt Forest, Surrey (SU804424) at 51°N latitude and is at Stop 4 on the Adaptation Trail (Figure 1). The trial was set up on the 1st February 1965 to test different provenances of RSQ from its north-south range in contrasting conditions in southern England, and to test for any differences in frost resistance. The trial consisted of planting 10 seed origins—each represented by 15 seedlings (except origins 1001 and 1011 with 14)—sourced from 7 provenances. For each seed origin, seed was collected from a single tree. Seedlings were planted in a non-randomized arrangement with 11 feet between each seed origin row and 8 feet between seedlings within rows (Figure 2). The seed was supplied by the University of California, and each provenance was named after the relative location along the West Coast, USA from which it originated. The species' range extends from just inside southern Oregon (42°N) to Gorda (35°N) in southern California, spanning almost 7° of latitude. This gradient is of particular provenance interest, as its southernmost populations represent the warmest origins that might still be climatically suitable for lowland planting in the UK. These populations may offer traits that support future resilience—such as faster growth or drought tolerance—but they also sit near the threshold of cold tolerance. Their adaptation to milder climates means they may be more vulnerable to frost and seasonal misalignment in the UK, especially in colder or more variable conditions (AH147 Experiment Plan, 1965). There is currently very little published research about the coast redwood species within a UK climate, however a report assessing the first 7 years of growth of the AH provenance trial compared to two other provenance trials in England has been published (Jinks & Kerr, 2016) which is built on in this report. In October 2024, 15 of the 61 surviving trees were thinned to reduce competition and to encourage the growth of understory plants to increase stand biodiversity. During the thinning operations, we took the opportunity to take a range of measurements and samples to help further understand how coast redwood grows in a southern UK climate.

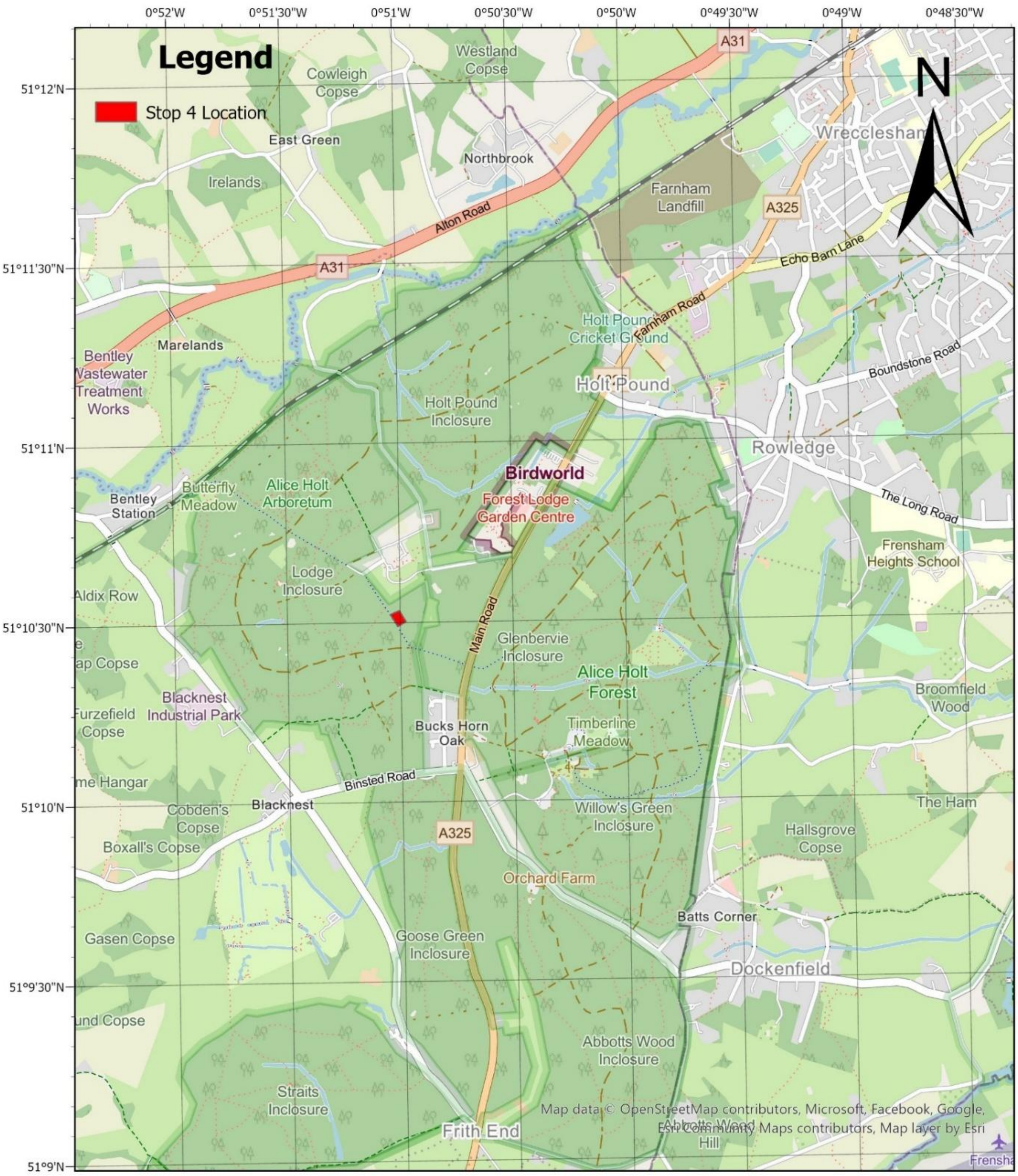

Figure 1 - The Location of the coast redwood provenance trial (AH147) in Alice Holt Forest, Surrey.

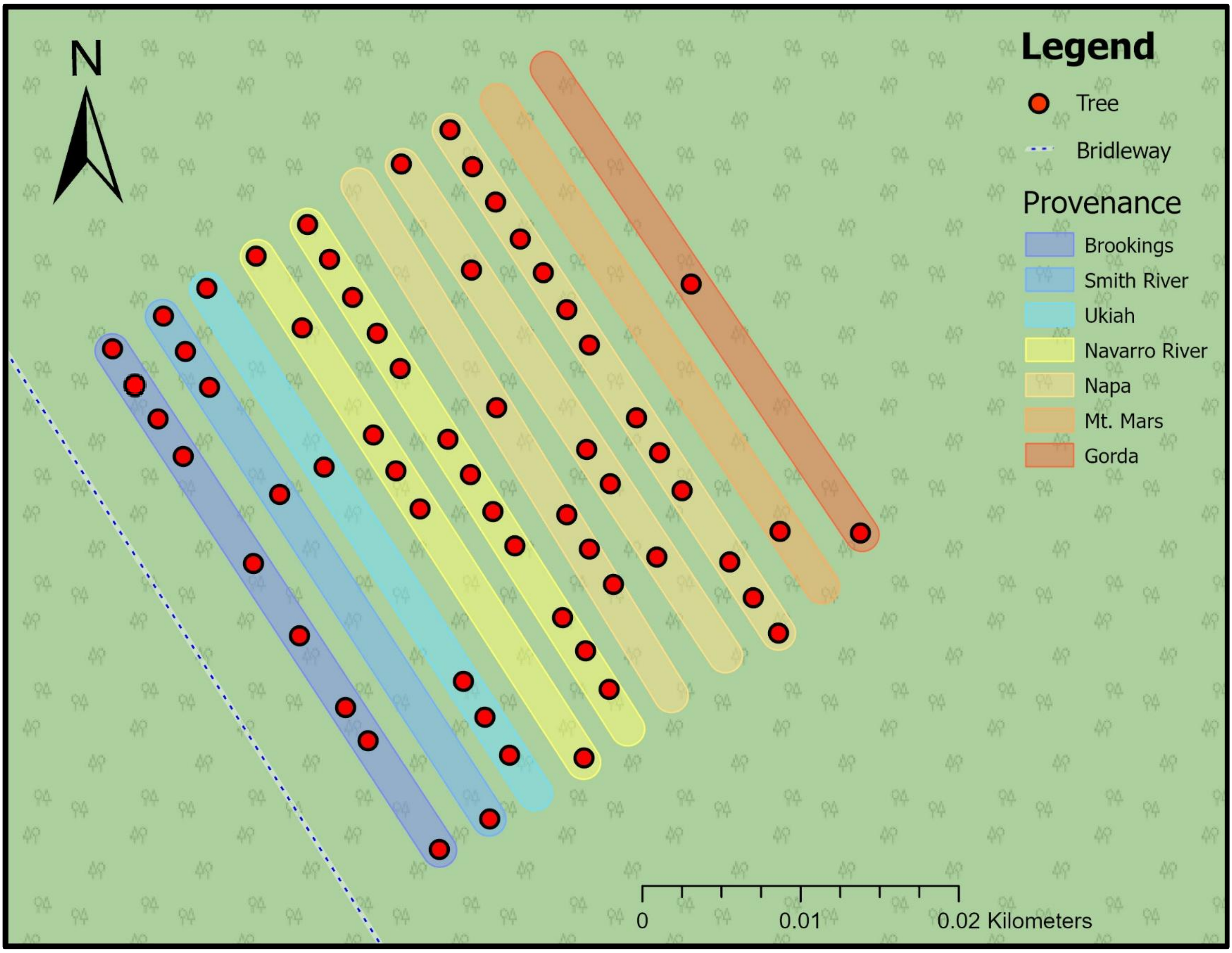

Figure 2 - The layout of the Alice Holt coast redwood provenance trial (AH147) and surviving trees as of October 2024. The provenances have been plated in rows of ~15 trees across its north-south range, with the most northerly provenance starting at Brookings, to the most southerly provenance at Gorda.

2.2.2 Other provenance trials

In 1965, dendrologist A.F. Mitchell set up two provenance trials using 10 & 11 RSQ seed sources at the Alice Holt (AH147) and Devon (Plym 3) sites, respectively. In 1968, another origin trial was set up at Weston Common near Alton (Alton 24) using 9 different seed sources from some of the same seed origins as well as other ones received in 1963. Below is a table (Table 1) of the provenances planted at each seed origin trial site and a map (Figure 3) of the location of each provenance. The data from the three trials was inconsistently gathered and limited to the first seven years after planting, making it difficult to draw firm conclusions about provenance-related variation in frost resistance. However, the information offers insights into frost and herbivore damage, weeding issues, and some frost-related mortality. Therefore, revisiting these trials could help better understand the way in which coast redwood and its provenances have performed in relation to frost resistance and drought tolerance over time. Information on the condition of the Alton 24 and Plym 3 trials is given in Appendix A; the analysis in this report is only for the AH 147 trial.

Table 1 – Location of RSQ provenances and seed origins in 3 provenance trials, listed from N to S. The number of existing trees in October 2024 (pre-thinning) have been added against AH147.

Provenance Location	Seed origin number	Alice Holt 147	Plym 3	Alton 24	Location Coordinates (DM)
Brookings (Southern Oregon)	1001	✓ (9)	✓		42°04’N 124°15’W
	1003		✓		
Smith River (Northern California)	1004		✓		41°56’N 124°08’W
	1005	✓ (5)	✓	✓	
Gasquet	3			✓	41°50'N 123°58'W
Richardson Grove	1			✓	40° 1'N 123°47'W
Ukiah	1007			✓	39°10’N 123°12’W
	1008	✓ (5)	✓		
	1009		✓	✓	
Navarro River	1010	✓ (6)	✓	✓	39°10’N 123°15’W
	1011	✓ (12)			
Napa	1016	✓ (4)	✓	✓	38°21’N 122°17’W
	1017	✓ (5)	✓		
	1018	✓ (13)	✓	✓	
Monterey	2			✓	36°36'N 121°53'W
Mt. Mars	1025	✓ (1)			35°48'N 121°20’W *
	1026		✓		
Gorda	1029	✓ (2)			35°52'N 121°26'W

* Mt. Mars is the most southerly provenance and has previously been referred to as Mt. Maro in the more recent report. Both Mt. Mars & Gorda originally did not receive coordinates to their location but have later been referred to as “Both are about 35°50'N” in latitude; their latitudes have now been more accurately noted.

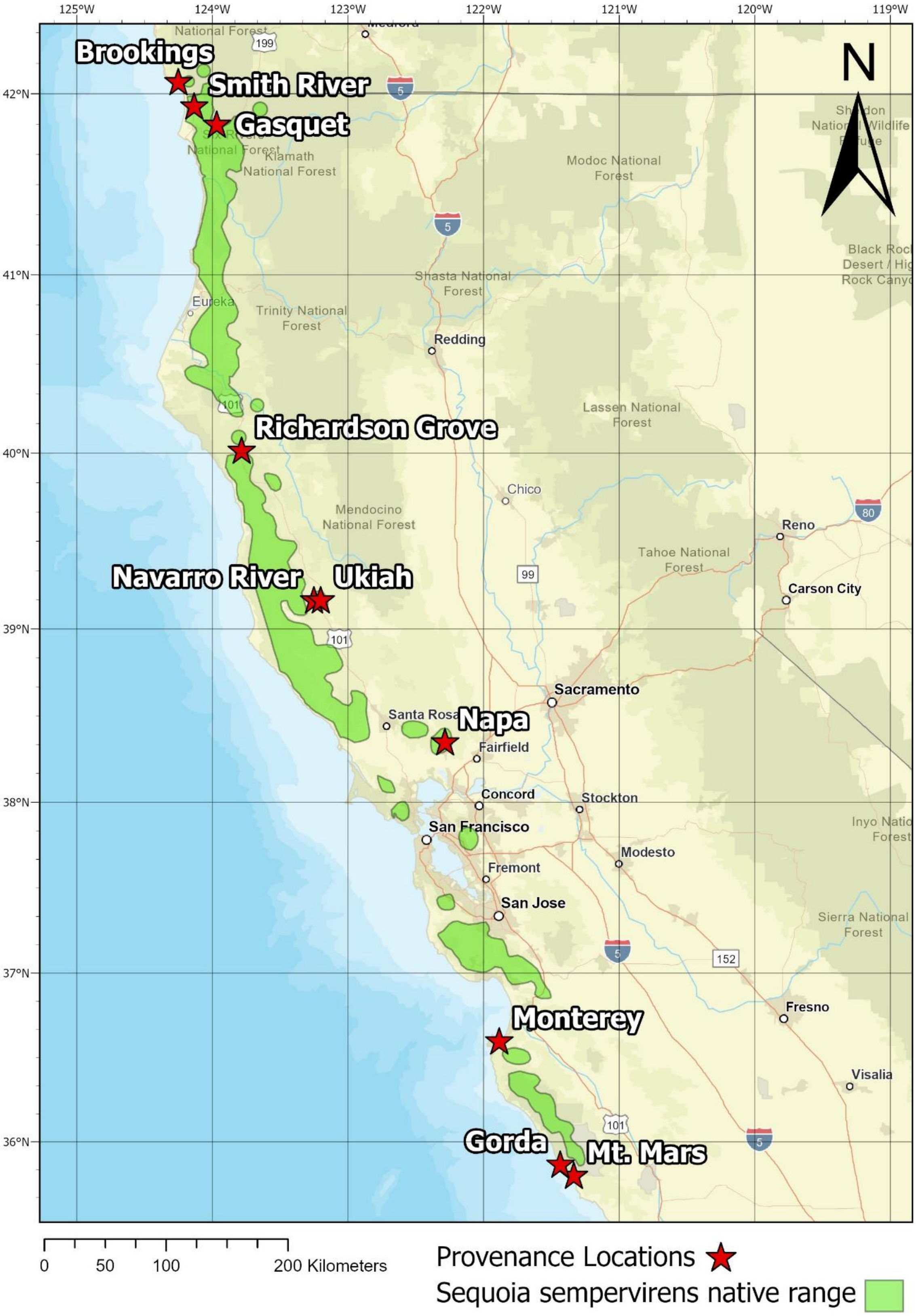

Figure 3 - A road map of the West Coast USA depicting the species native range and where each coast redwood provenance was sourced from (approximately).

2.3 Aims and Objectives

This pilot study aims to begin understanding the influence of climatic variables on the growth of coast redwood provenances in a southern UK climate, and to assess which provenances may be best suited to future climate conditions and associated risks. Using data from the AH 147 trial, key growth characteristics—such as survival, growth performance, bark thickness, and dendrochronological patterns—will be examined. Analysis will provide insights into how these provenances respond to climatic variability.

This aim can be achieved through the following objectives:

1. To analyse the annual growth rings to determine growth patterns and climatic influences, particularly drought sensitivity.
2. To evaluate the survival rates in a UK climate over a 60-year period, providing evidence of frost intolerance as a limiting factor for establishment and long-term viability. This will help assess which provenances are more capable of withstanding cold extremes typical of the UK climate.
3. To investigate the variation in bark thickness among provenances and its change with height, as bark thickness is a key adaptive trait linked to wildfire resilience. Understanding this variation can inform selection of provenances with greater potential to withstand fire-related disturbances under future climate regimes.

3 Methods

3.1 Growth and survival

Each tree was given a unique reference code to ensure accurate tracking and data collection (Figure 4). Tree growth was calculated using height and diameter at breast height (DBH) measurements, whilst survival was determined using a tree count. The DBH and survival of all trees were recorded in October 2024 and added to the existing dataset, which includes survival measurements taken on the following dates: 03/03/1965, 02/11/1965, 25/10/1966, 31/03/1967, 07/05/1971, 14/11/1979, and 24/02/1982. Additionally, the two most southern provenances Mt. Mars & Gorda, were only included in the survival analysis, as only 1 and 2 trees remained respectively.

DBH was measured at 1.3 m height using a 5 m diameter tape, and tree heights were recorded for approximately one third of the trees using a Haglöf Vertex 5 and T4 transponder, calibrated over a 10 m ground distance. These measurements were conducted in accordance with standard operating procedures SOP0093 (Use of measuring tapes) and SOP0237 (Use of the Vertex III hypsometer and T3 transponder).

Of the 15 trees removed during thinning, top height and DBH measurements were successfully recorded for 9 trees. Height was measured using a 50 m measuring tape once felled, and DBH readings were taken at the base of each tree (10–40 cm) and at 3 m intervals following the standard DBH measurement at 1.3 m. Limited data collection for tree heights and thinned trees was due to accessibility challenges and time constraints in the field, which prevented full measurement of the stand.

3.2 Bark thickness

To examine how bark thickness changes along the stem, bark thickness (BT) measurements were conducted on the 15 thinned trees (Figure 4). Measurements were taken at the same intervals as the DBH measurements: at the base (10-40 cm) and at DBH height (1.3 m) for all 15 trees. Additionally, for 9 of the 15 trees, measurements were then taken at 3-meter intervals along the stem from 1.3m to the top of the tree, following the methodology of Berrill et al., 2020. At each interval, four BT measurements were taken at the north, east, south, and west-facing positions of the tree. To maintain consistent orientation, the north and west directions were marked with blue and white spray paint, respectively.

BT measurements were taken with a 5cm Haglof Bark Gauge once a change in pressure was felt as the chiselled end of the gauge penetrated the wood interface. Due to the fissured nature of the redwood bark, readings were taken on ridges, making sure that the gauge was flush to the bark before reading.

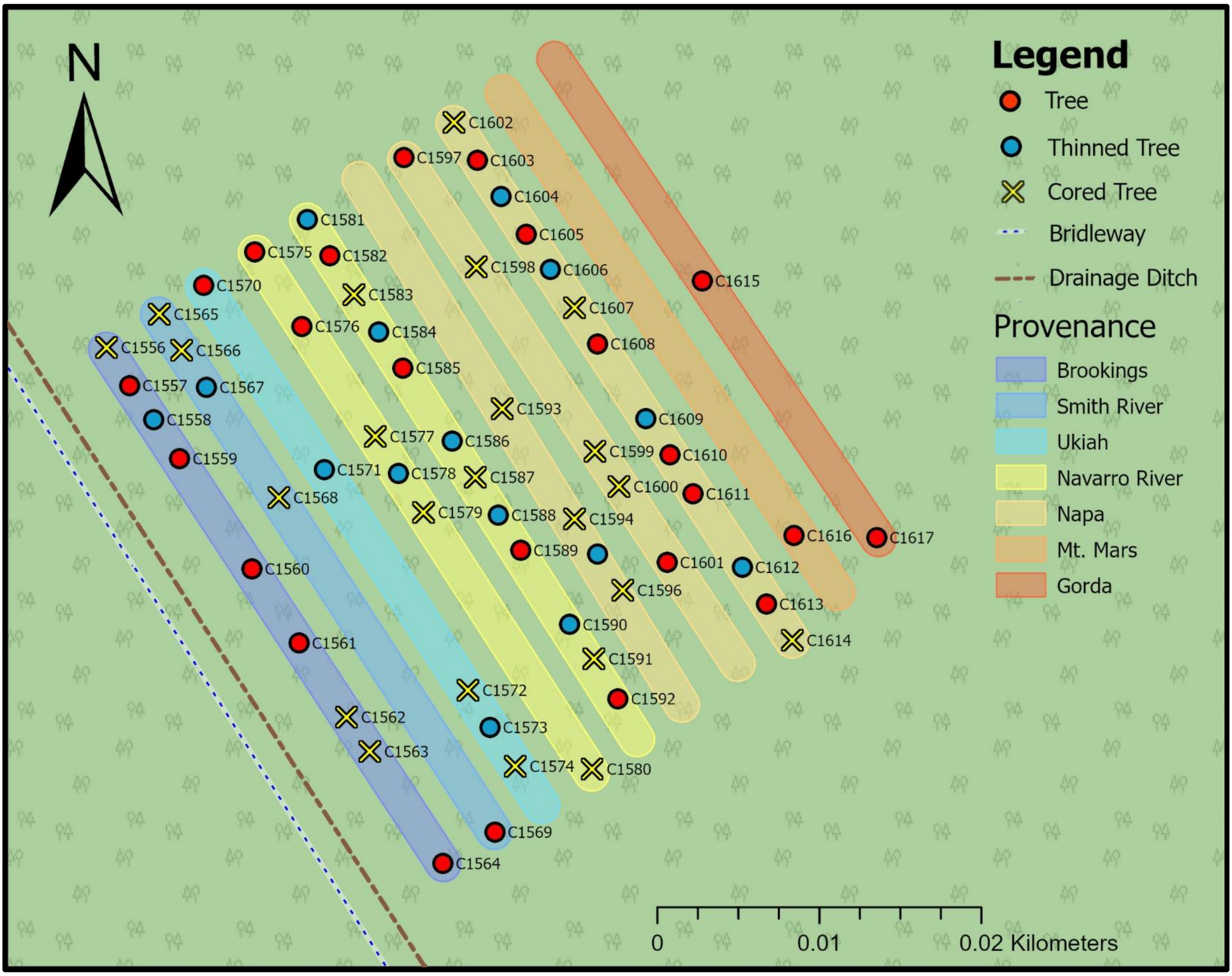

Figure 4 - Map showing the location of each tree at the AH 147 RSQ trial, including its unique reference code and whether it was thinned or cored.

3.3 Dendrochronology

In October 2024, increment cores were extracted from 23 trees from the AH147 trial, marked as cored trees (Figure 4). Two increment cores were extracted from opposite sides of each tree at DBH with a 5.15 mm diameter increment borer (Hägloff), resulting in a total of 46 tree-ring increment cores collected. After extraction, increment cores were stored in paper straws and transported to the DendroLab at NRS for analysis. In the lab, samples were air-dried and then permanently mounted in grooved wooden holders using water-soluble wood glue.

3.3.1 Tree Ring Measurement and Analysis

To enhance the visibility of ring boundaries and ensure a smooth, planar surface across each core, a WSL core microtome was used for surface preparation. Samples were then scanned using an Epson Expression 12000XL scanner. Tree-ring widths (TRW) were measured in the radial direction, from bark to pith, to the nearest 0.001 mm using CooRecorder software (Larsson, 2013). Each sample was cross-dated and verified both visually and statistically using CDendro software (Larsson, 2013), followed by further analysis using the dplR package in R (Wickham et al., 2023). The number of samples per tree provenance included in the final analysis is presented in Table 4.

3.3.2 Tree Ring-Width Standardisation and Chronology Development.

Cross-dated raw series were standardised to remove the influence of the age-related trend typically present in raw ring width measurements, using the dplR package. A spline function with a 50% wavelength cut-off corresponding to approximately 20% of the series length was applied to the raw data. This approach removes long-term trends (such as those related to age and growth trends) while retaining inter-annual variability, thereby preserving high-frequency variations relevant to climate–growth analyses. The ring-width chronology was then developed, using the dplR function, which builds a mean value chronology, typically from a data frame of detrended ring indices across the series for each year. A ring width chronology was then developed for each provenance. The strength of the common signal within the chronologies was assessed using the Expressed Population Signal (EPS) statistic. As is commonly practised, the EPS value should exceed the threshold of 0.85, indicating a sufficient strength of the common signal within the time series. When the EPS falls below this threshold, the chronology becomes increasingly influenced by individual tree-level signals (Neupane et al., 2023).

Additional chronological statistics, including the standard deviation, mean sensitivity, series intercorrelation, autocorrelation, and mean inter-series correlation (Rbar), were also calculated. Mean sensitivity quantifies the year-to-year variability within the master chronology. Mean sensitivity value of approximately 0.2 is generally considered sufficient to indicate that the series is responsive enough for climate reconstruction (Neupane et al., 2023) (Neupane et al., 2023). The Rbar statistic represents the average correlation between all possible series pairs within overlapping 20-year windows. It serves as a running measure of the percentage of shared variance, reflecting the strength of the common signal. Series intercorrelation reflects the site-level signal, with values above 0.50 generally desirable, though a threshold of 0.32 is commonly accepted due to variation by species, location, and climate (Neupane et al., 2023).

3.4 Climate data

Daily climate data were acquired from the met station at Alice Holt Lodge 300 meters from the trial site.

Up to 2012, the daily observations were manually measured, and since then the data has been recorded using digital sensors. However, there is a 10-year span of missing data between 2002 and 2012. The overall dataset contains temperature (minimum, maximum, and average), total rainfall, and windspeed. This data was used to assess the climate conditions experienced by the RSQ during the first and last seven years of the trial.

Alternatively, 1km resolution gridded UKCP18 data was sourced from The Centre for Environmental Data Analysis (CEDA) archive using the site grid reference - SU804424 to provide a more consistent and continuous dataset of monthly climate data (Met Office, 2003). Average temperature, precipitation and the Standardized Precipitation Evapotranspiration Index (SPEI) data were used to understand the influence of climate on tree growth over time to highlight periods when it was sensitive to specific climatic conditions.

3.4.1 Climate growth response.

To quantify the climatic drivers of radial growth, we employed the dcc function from the treeclim package in R (Zang & Biondi, 2015). This function computes both response (static) correlations and moving-window correlations (20-year window) between residual chronologies and climate variables, thereby allowing the detection of temporal shifts in climate–growth relationships. Given that climatic conditions in the year preceding ring formation can influence subsequent growth, we evaluated, for the entire analysis period, correlations between annual ring width and monthly climatic variables from May of the previous year to October of the current growth year.

4 Results and Discussion

4.1 Survival at AH

Over the 60-year period, a total of 41% of the trees that were planted have survived in a southern UK climate at Alice Holt. Figure 5 shows the change in tree survival per provenance for the AH 147 stand from 1965 to 2024 (pre thinning) and highlights where tree losses occurred at certain ages per provenance. During the first seven years of growth, between 03/03/1965 (age 0.1) and 07/05/1971 (age 6.3), the stand experienced its highest mortality, losing 56% of trees — a total of 82 individuals. The two most southern provenances, Mt. Mars and Gorda, were hit hardest, losing 93% and 86% of their trees respectively, with only one and two individuals surviving. Other provenances such as Smith River and Ukiah also suffered significant losses, each exceeding 50% mortality during this period. After 1971 (age 6.3) mortality dropped dramatically — only five trees were lost from that point onward. This suggests that survival improves markedly once redwoods reach a certain age, possibly due to a combination of physiological resilience and reduced competition from neighbouring trees lost during the early establishment phase. Meanwhile two mid-range provenances, Navarro River and Napa, showed survival rates around 50%, performing nearly as well as, or even better than, the most northern provenance, Brookings, from the same starting age of 6.3 years. Given that Navarro and Napa are approximately 450 km south of Brookings, this challenges the assumption that more northern or climatically similar provenances should perform better in cooler environments.

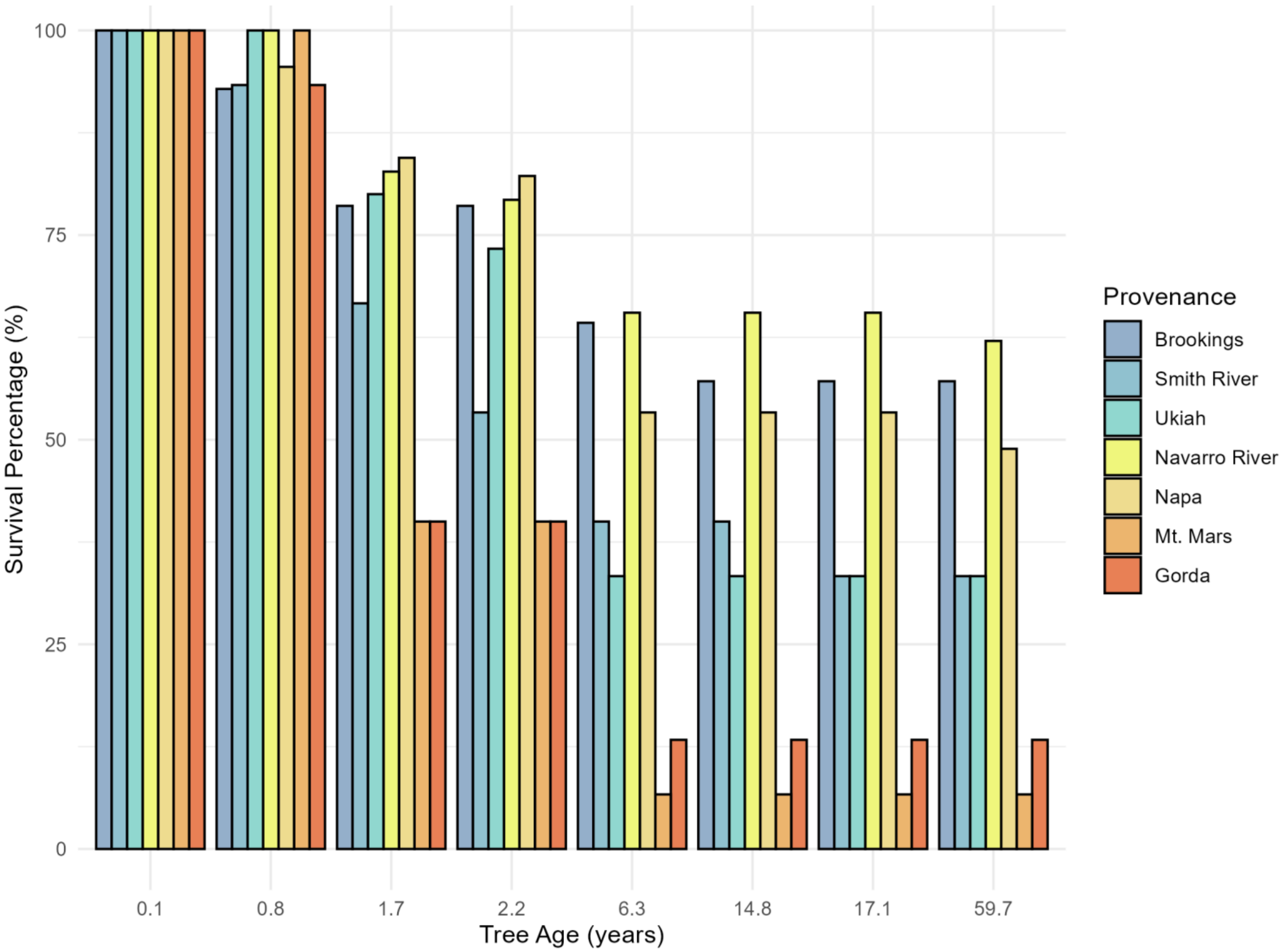

Figure 5 - A graph of the survival rate for each provenance of the AH147 trial at different intervals between 1965-2024

4.2.1 Frost Resistance

As was the initial objective of the trial, we attempted to determine if there were any differences in apparent frost resistance between provenances. We have defined frost as is stated by Copernicus (2021), where frosts for forestry are close to the ground, sub-zero temperatures that occur in spring. Within the USDA plant hardiness zones that encompass the natural range of coast redwood, these trees typically experience only light frosts for a few weeks each year, with minimum temperatures ranging from -4°C to 5°C (Breidenbach et al., 2020). As young RSQ are particularly vulnerable to frost, especially in spring (Roy, 1966), we focus on the first seven years of survival, which is the period that the survival data above (Fig. 5) indicates is critical for early establishment. We examined how frost incidence and severity relate to the differential survival rates observed among provenances. To identify late spring frost events, daily minimum screen air temperatures from the nearby AH met station from January to May between 1965 and 1971 were plotted and categorized into three severity thresholds: <= 0.0°C, <=- 2.0°C, and <=−4.0°C, (Figure 6). The −4°C threshold was selected to represent frost events that exceeded the typical tolerance range defined by the USA hardiness zones and may therefore capture the more severe events with a higher likelihood of physiological stress, damage or mortality. The −2°C threshold was chosen to reflect the point at which frost damage may begin in frost sensitive species like RSQ and may cause sub-lethal frost stress that could impact growth and survival (Atucha-Zamkova et al., 2021).

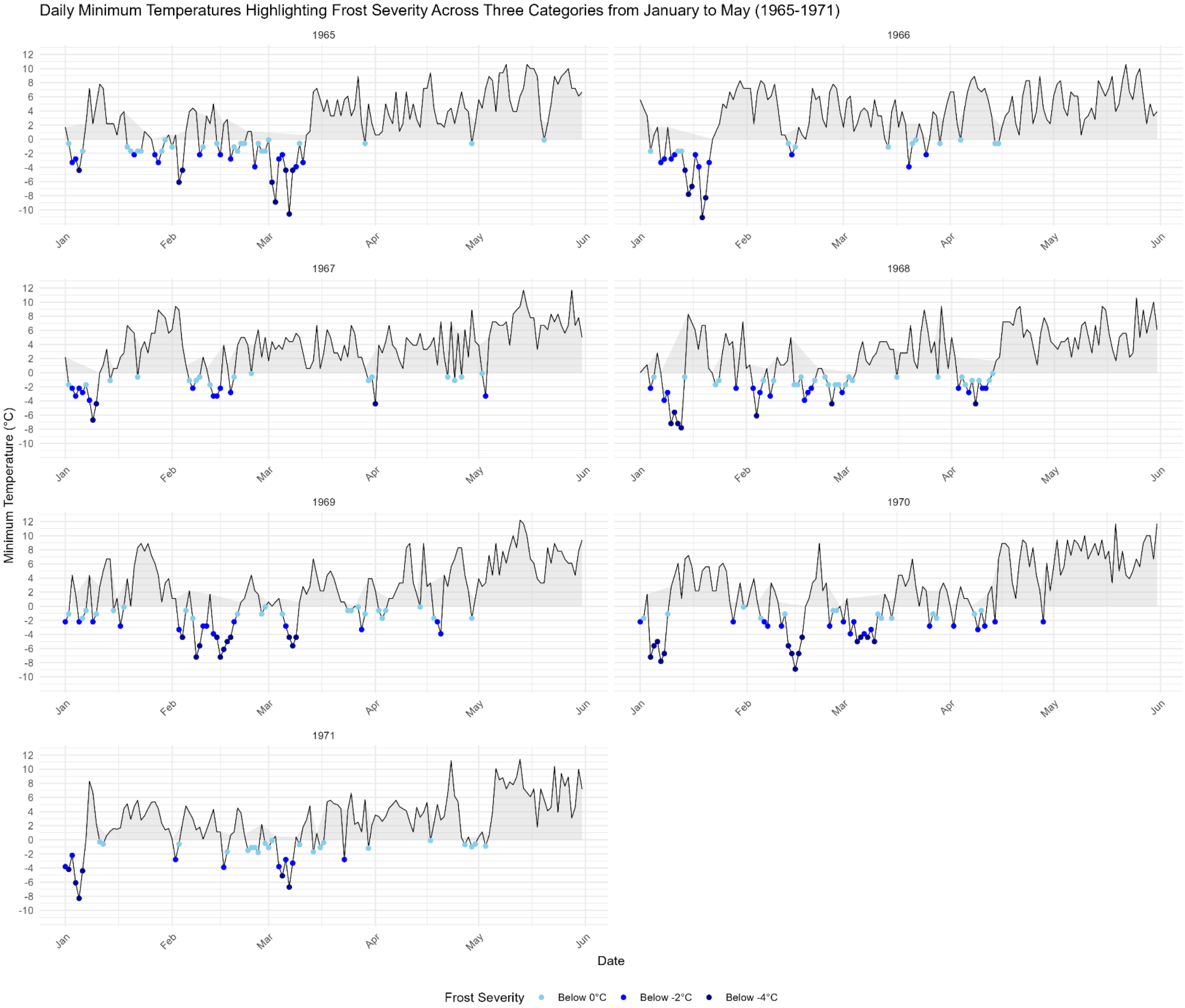

Figure 6 - Graphs depicting spring frost incidence and different severities from January to May for the first 7 years of growth of the AH147 stand; daily minimum temperature data from the AH meteorological station.

Table 2 - A table showing the number of spring air frost events (March – May) and their different severities for the first 7 years of growth of AH147 (1965-1971).

Year	Frost < 0°C	Frost < -2°C	Frost < -4°C	Total number of frosts
1965	5	4	5	14
1966	9	2	0	11
1967	6	1	1	8
1968	12	4	1	17
1969	13	4	3	20
1970	10	11	4	25
1971	12	4	2	18
Total	67	30	16	113

During the spring periods (1st March – 30th May) from 1965 to 1971, Table 2 shows the total number of spring air frost events of different severity per year. Over these seven years, a total of 113 spring frosts were recorded. Of these, 59% were mild frosts (< 0°C), 27% were moderate (< -2°C), and 14% were severe (< -4°C). 1970 experienced the highest number of spring frosts, with 25 events, while 1967 had the fewest, with 11 and 8 respectively. Notably, 1965 recorded the highest number of severe frosts (< -4°C), with 5 events, whereas 1966 had none. Frosts in 1965 were more evenly distributed across all three severity categories, whereas 1970 stood out with a notably higher number of moderate frosts—11 events below -2°C—compared to other years.

To analyse the relationship between the number and severity of spring frost events and the survival rate of each provenance at different measurement ages, additional information on the timing of the seasonal transition of trees from dormancy to active growth, —currently not readily available for coast redwoods—would be required (Atucha-Zamkova et al., 2021).

To determine the onset of the growing season, the date of first budburst or new shoot growth must be observed, which can serve as a reference point for calculating cumulative Growing Degree Days (GDD) (Svystun et al., 2021).

The accumulated GDD required to reach budburst provides a valuable metric for identifying when coast redwood is most vulnerable to late spring frosts. Integrating this phenological data with frost event records would allow for a more precise assessment of how frost timing and severity influence early survival between different provenances.

Under current and projected future climates, it is likely that we will experience fewer frosts. This trend is highlighted in *The State of the UK Climate 2024* report, which shows that the most recent decade (2015–2024) had over 14 fewer air frost days per year compared to the 1961–1990 and 1931–1960 periods (Kendon et al., 2025). This shift is also evident in the air frost data at AH over the past seven years (2018–2024). Figure 7 illustrates the frequency and timing of frost periods from January to May, while Table 3 shows a reduction in spring air frosts (March - May) from 113 to 91 compared to the 1965–1971 baseline. Notably, the number of severe frosts has declined significantly—from 16 to 5 (a 68.75% decrease). This aligns with Kendon et al., (2025), who report a 28% and 50% reduction in the average number of days per year with daily minimum temperature anomalies below 0°C and −5°C, respectively.

2024 recorded the lowest number of frosts in the UK since records began in the 1930s, further underscoring the impact of a warming climate (Kendon et al., 2025). However, the data also reveal variability: 2021 had the highest number of frosts among the seven years in Table 3, highlighting how frost risk remains unpredictable and localized for the future.

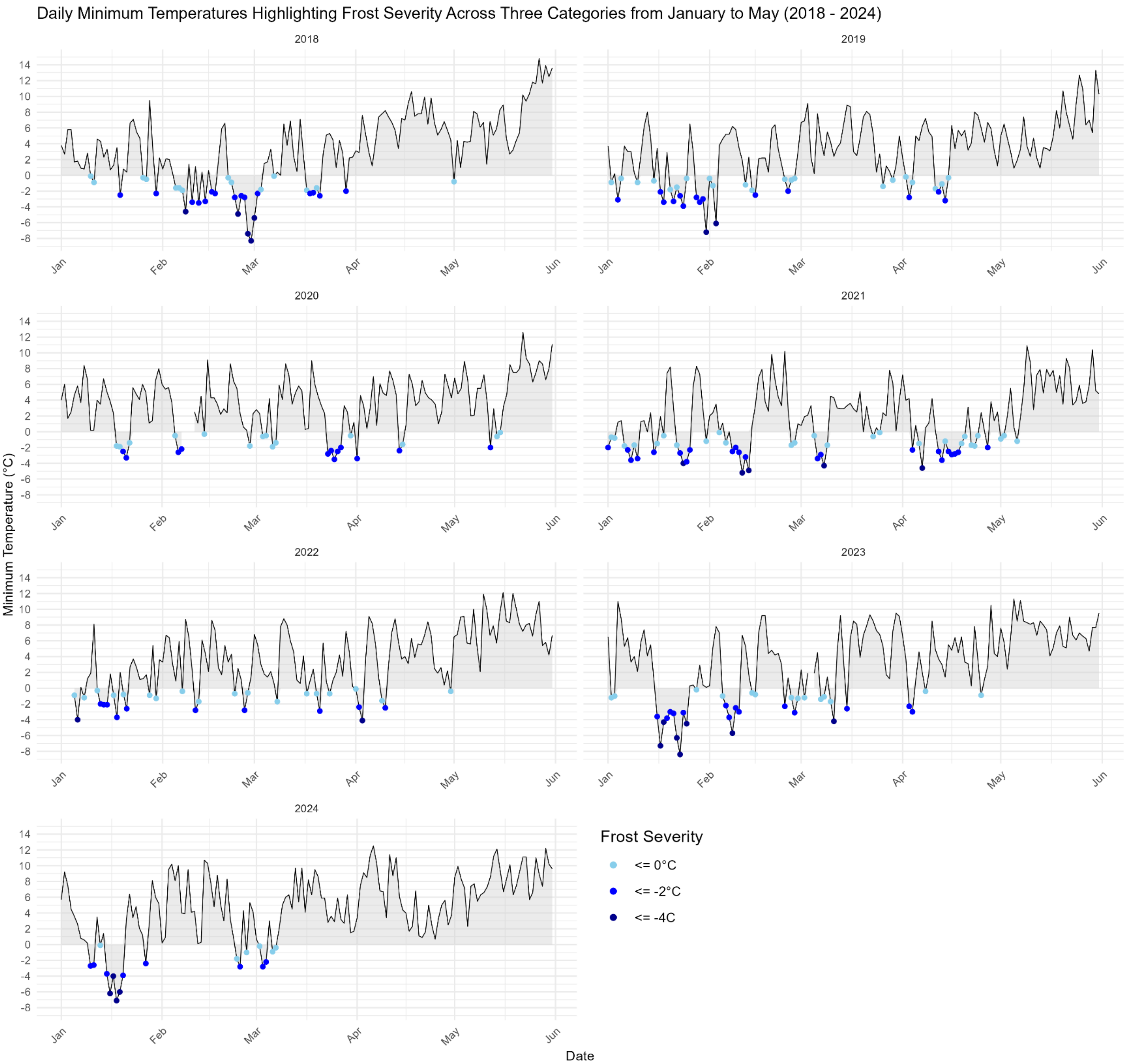

Figure 7 - Graphs depicting spring frost incidence and different severities from January to May for the last 7 years of growth of the AH147 stand; daily minimum temperature data from the AH meteorological station. *There are 7 missing measurements within the frost dataset (8th–10th February 2020, 2nd–4th January 2022, and 3rd April 2023)*

Table 3 - A table showing the number of spring air frost events (March – May) and their different severities for the last 7 years of growth of AH147 (2018-2024).

Year	Frost < 0°C	Frost < -2°C	Frost < -4°C	Total number of frosts
2018	6	5	1	12
2019	7	3	0	10
2020	8	8	0	16
2021	15	10	2	27
2022	7	3	1	11
2023	6	3	1	10
2024	3	2	0	5
Total	52	34	5	91

4.3 Bark Thickness

Figure 8 shows the changes in average bark thickness (BT) with height of 9 trees felled in October 2024. The general trend is a gradual decrease in BT as the height of the trees increase, decreasing from ~4cm at the base to ~0.5cm by 26m. However, the BT is highly variable both within and between individual trees at different heights, with increases of up to 0.8cm at the next height increment - potentially due to buttressing and irregular stem form. The general trend observed in Figure 8 aligns with the findings of Berrill et al. (2020), which also show a decrease in BT with increasing tree height. Unfortunately, the limited sample size means provenance comparisons could not be made.

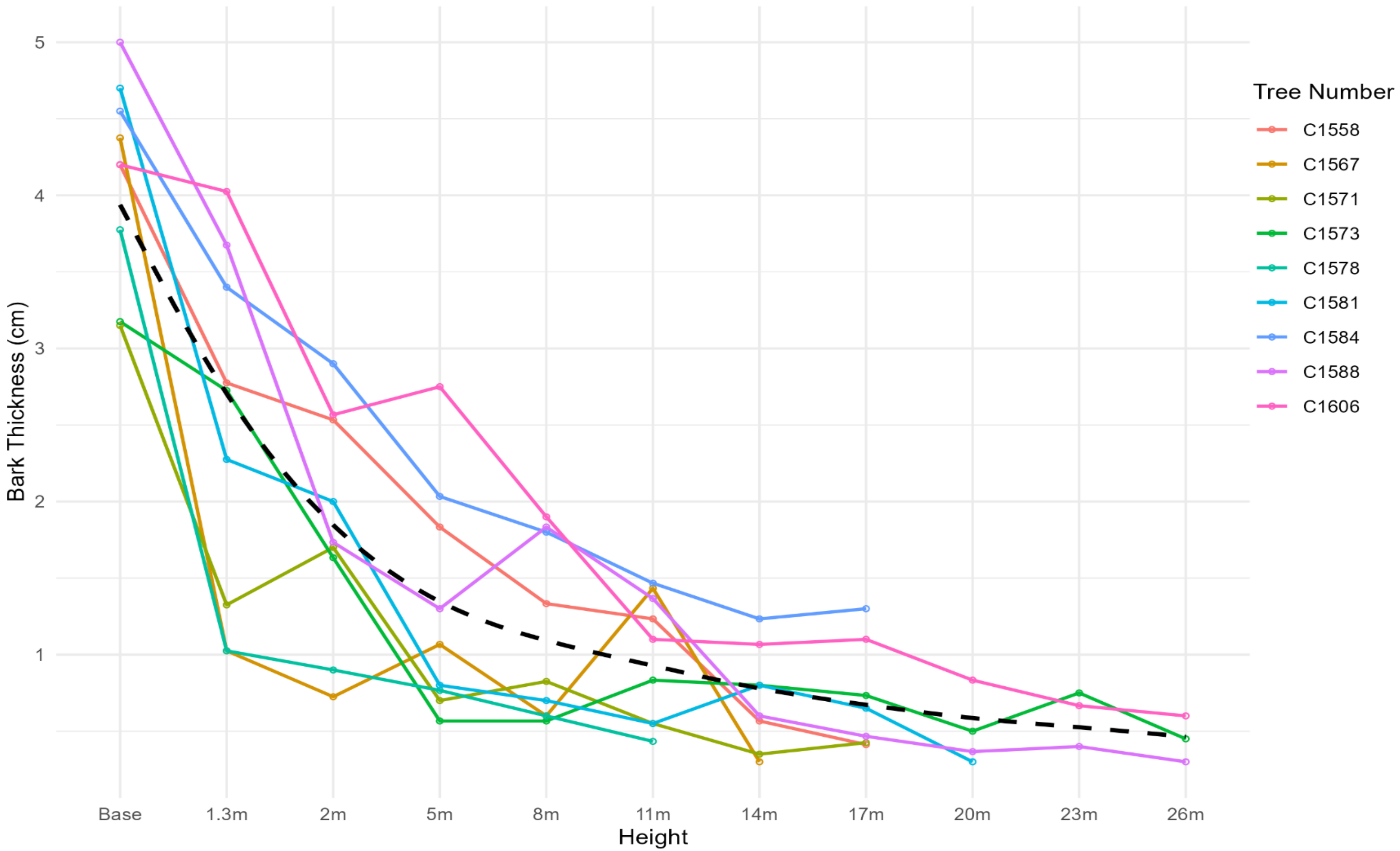

Figure 8 - A graph showing the average bark thickness at different heights for the 9 RSQ trees that were thinned in AH147

4.4 Dendrochronology

4.4.1 Cross dating results

A seed origin Coast Redwood chronology was developed from 40 successfully cross-dated samples obtained from 21 trees. Table 4 presents the descriptive statistics for each provenance.

Table 4 - A table showing a number of descriptive parameters from the dendrochronological measurements for each remaining seed origin in the RSQ trial AH147.

Parameters	**Seed origin**							
	1001	**1005**	**1008**	**1010**	**1011**	**1016**	**1017**	**1018**
No. of trees	3	3	2	3	3	2	2	3
Overall period	1968-2024	1973-2024	1971-2024	1974-2024	1968-2024	1972-2024	1972-2024	1970-2024
Age (years)	56	51	53	50	56	52	52	54
Overall number of measurements	164	151	101	146	159	104	104	154

The measured tree ring widths from the increment cores were initially dated to 2024, corresponding to the sample extraction date in October 2024. Where the cross-dating procedure identified measurement errors (e.g., correlation coefficient was too low for valid dating in 2024), the sample was reprocessed from the measurement stage. Errors were rectified by adjusting the ring count (shifting, adding, or removing rings). Following this editing, time series that did not match correctly were excluded from the analysis. Only individual time series that satisfied the agreement coefficient criteria were included for further analysis. Initially, the best samples for each orientation (north or south) from each tree, prioritising those with both pith and bark and without breaks, were compared against each other using the cross-dating process in CDendro. If these criteria were met, the cross-dated tree-ring widths (TRW) were added to the primary collection. Secondly, the TRW were combined to create a *Coast redwood* chronology.

Subsequently, any remaining samples lacking pith, bark, or exhibiting breaks were matched against this chronology. If the cross-dating procedure did not detect measurement errors and the agreement coefficient was satisfactory, these time series were incorporated into the chronology. The TRW were also cross dated in dplR.

Tree-ring width and dendrochronological statistics were initially processed at the seed origin level to retain the highest resolution of genetic and environmental variation. These seed origins were subsequently grouped into seven provenances for the purposes of standardization, BAI comparisons and climate-growth analysis. This hierarchical approach allows for both fine-scale quality control and broader dendroclimatic interpretation.

Figure 9 shows the annual tree ring width for each seed origin which ranges from between ~1mm to ~12mm of growth each year. The TRWs highlight how all seed origins exhibited moderate variability and occasional synchronous reductions across the dataset. This indicates a shared response to broad-scale environmental drivers. However, following 1990 after a sudden drop in growth, a divergence in growth trajectories emerged, with 1001 and 1005 exhibiting consistently wider rings in recent years. This pattern may reflect edge effects potentially driven by increased light exposure and water availability due to the adjacent bridleway and drainage ditch on the west side of the stand. The TRW chronologies exhibited a consistent pattern of sharp growth declines in specific years—most notably 1976, 1990, 1995, 2003, 2013, and 2022—often followed by a recovery in the subsequent one to two years. This pattern suggests a shared sensitivity to climatic stressors, such as drought. However, recovery was not always immediate. In particular, the periods following 2003–2005 and 2018–2021 were marked by slower or more variable rebounds in growth.

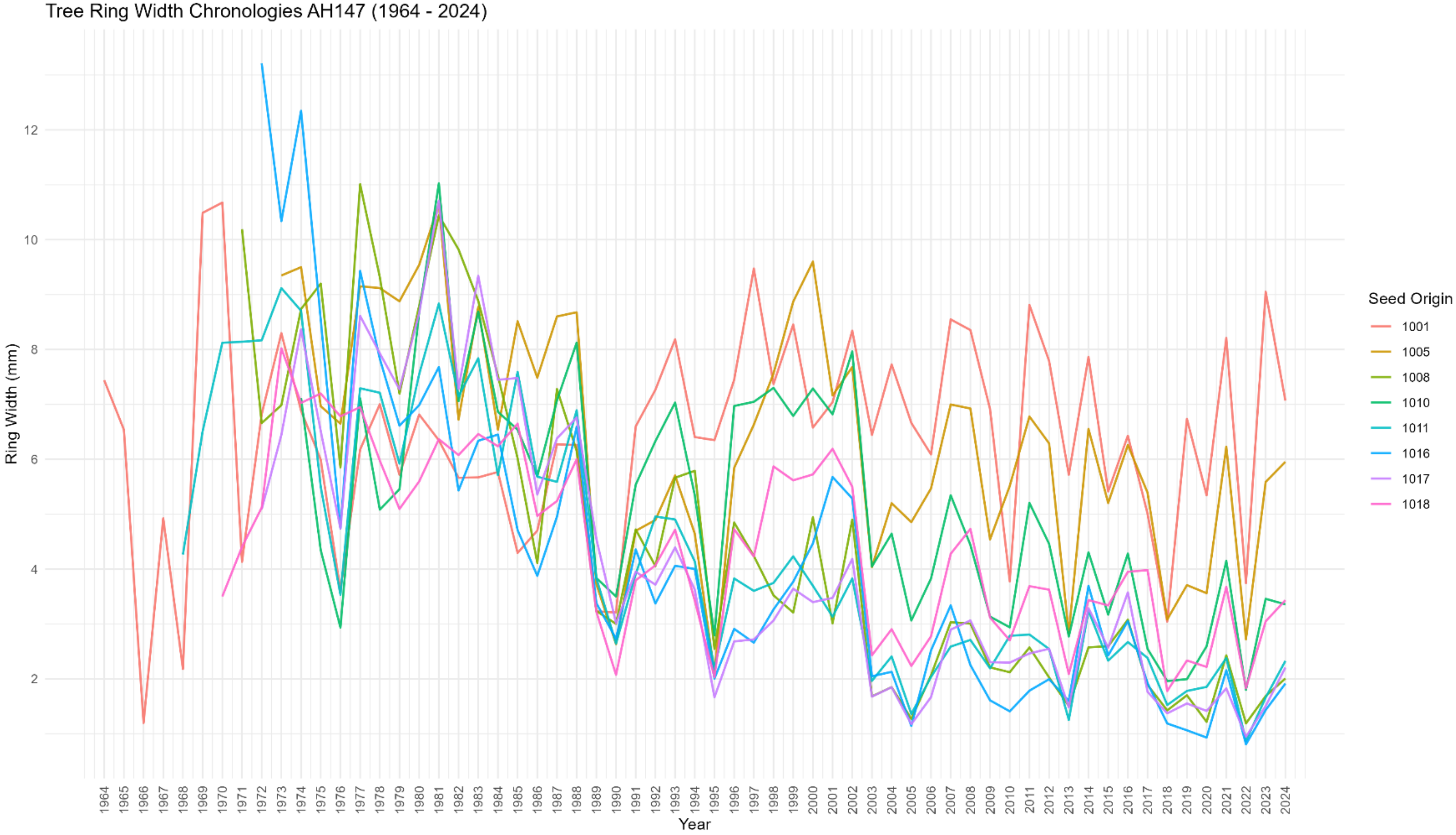

Figure 9 - Tree-ring width chronologies (1964–2024) for eight seed origins at AH147. Each coloured line represents annual tree-ring width (mm) for an individual seed origin.

4.4.2 Coast redwood Chronology

For the study period 1965–2024, mean sensitivity values (which reflect the degree of year-to-year variability in radial growth) across all seed origins ranged between 0.28 and 0.35, which falls within the usually accepted range. Series intercorrelation values for all seed origins exceeded the critical threshold of 0.32, with values above 0.5 considered indicative of a strong common signal. The mean Expressed Population Signal (EPS) values for seed origins 1005, 1010, and 1016 were 0.85, 0.86, and 0.85, respectively, all meeting the threshold of 0.85 required for a statistically robust chronology. Seed origins 1011, 1017, and 1018 had slightly lower EPS values of 0.81, 0.78, and 0.84, respectively, but remained close to the critical value. Rbar, a measure of the average inter-series correlation, quantifies the extent to which individual tree-ring series share a common signal, reflecting the degree to which trees respond similarly to shared environmental factors. Higher Rbar values (approaching 1) indicate strong coherence among series.

Table 5 - A table showing a number of descriptive statistics from the dendrochronological analysis for each remaining seed origin in the RSQ trial AH147.

	Seed origin							
Parameters	**1001**	**1005**	**1008**	**1010**	**1011**	**1016**	**1017**	**1018**
Series Intercorrelation	0.428	0.59	0.352	0.659	0.666	0.575	0.657	0.487
First-order autocorrelation	0.226	0.480	0.708	0.650	0.795	0.689	0.825	0.646
Mean Sensitivity	0.34	0.33	0.35	0.33	0.29	0.33	0.28	0.29
Expressed population signal (EPS)	0.66	0.851	0.608	0.868	0.817	0.854	0.788	0.845
SNR	2.125	5.73	1.88	6.58	4.60	7.37	4.56	5.44
Rbar	0.406	0.656	0.450	0.687	0.630	0.749	0.656	0.644

As the objective was to preserve as much inter-annual (high frequency) variation as possible in order to extract a climate signal, the time series were standardised using spline detrending via the dplR package. Standardising in this context refers to removing long-term growth trends—such as those caused by tree age or size-to isolate short-term fluctuations. The detrending process for each seed origin can be found in Appendix B.

The Ring Width Index (RWI) chronology for each seed origin (Figure 10) illustrates the growth trends following the application of spline detrending to the tree-ring width (TRW) series. As the differences between seed origins are minimal, Appendix C presents the provenance grouping of the RWI to better highlight geographic patterns in growth.

The standardised RWI values enable clearer observation of inter-annual variability in growth, which appears consistent between 1970 and 2024. Such variability suggests that tree growth was influenced by short-term environmental factors such as precipitation and temperature, with notable consistency across seed origins.

Notable reductions in tree ring growth, similar to those observed in the TRW analysis, occurred in 1976, 1989/1990, 1995, 2003/2005, 2013, 2018, and 2022, coinciding with documented drought events in the UK. These reductions, ranging from approximately 15% to 50% below the mean growth level for most seed origins, highlight the sensitivity of this stand to drought conditions, with further context provided in section 4.4.4.1 Drought-RWI of the report. The RWI values also show some periods of strong growth, particularly in 1988, 2002 and 2016 with most seed origins recording a RWI of close to 1.25 (+25%).

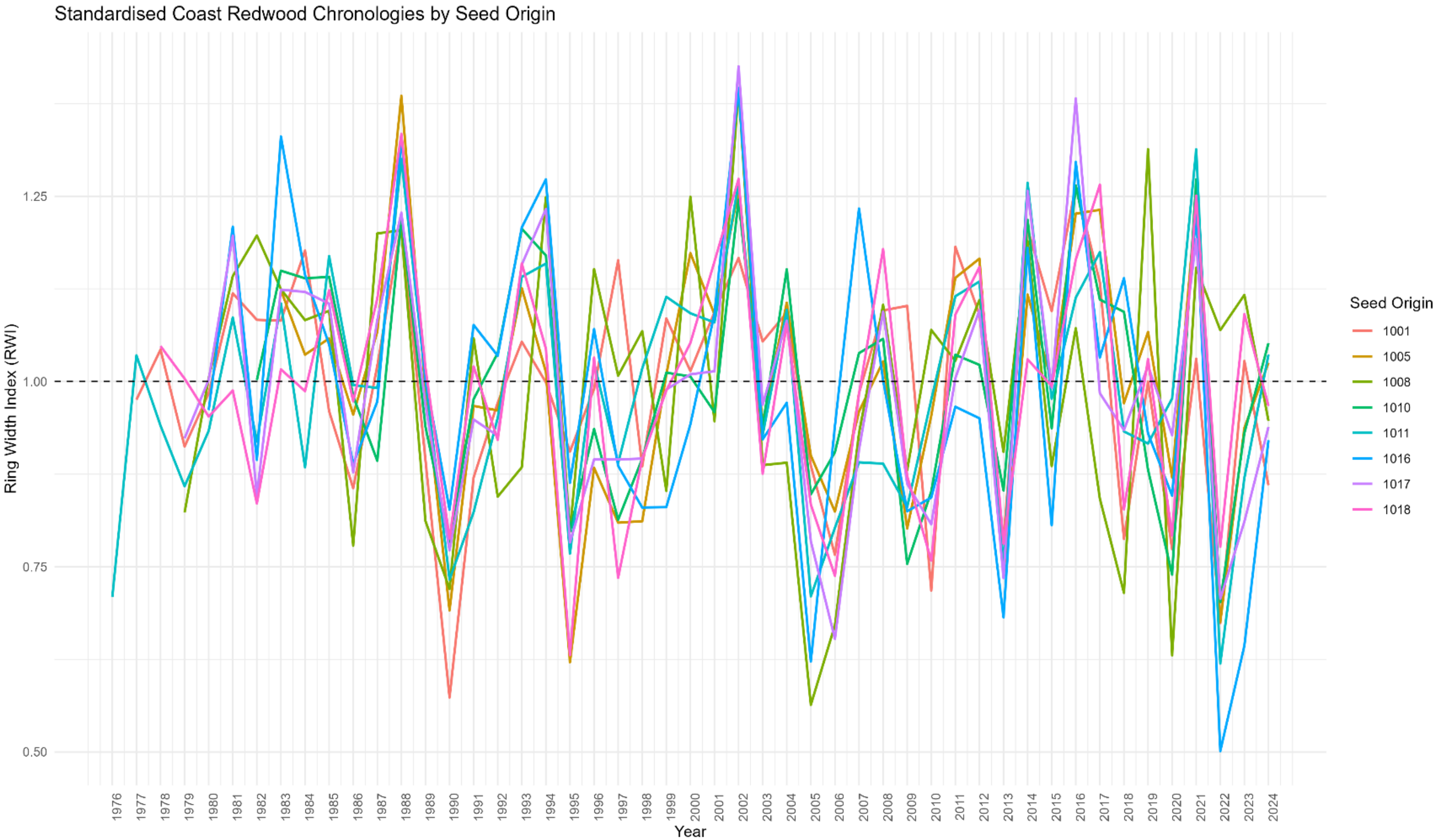

Figure 10 - Standardized chronologies for each RSQ seed origin from 1976-2024 in AH147 trial.

4.4.3 Basal Area Increment (BAI)

Basal Area Increment (BAI) is defined as the annual increase in the cross-section area of a tree trunk and provides a direct assessment of wood production and growth typically measured at 1.3 meters above the ground.
For most seed origins, BAI remained within 25–75 $cm^2\ yr^{-1}$, (Figure 11), with moderate interannual variability and occasional synchronous reductions, likely reflecting climatic effects. Growth trajectories for these seed origins were generally stable or showed slight increases over time, indicating consistent productivity under the site conditions. In contrast, seed origin 1001 and 1005 exhibited substantially higher BAI values, frequently exceeding 100 $cm^2\ yr^{-1}$ in recent years. This enhanced growth is likely attributable to the edge-related factors, including proximity to the small drainage ditch that channels water from the bridleway, thereby improving local water availability and potentially reducing competition stress.
Additionally, Figure 12 shows the distribution of BAI by provenance, further highlighting the significant growth observed in the two most northern provenances — Brookings (1001) and Smith River (1005) — with average yearly basal areas of approximately 86 and 76 $cm^2\ yr^{-1}$, respectively, and median values of around 78 and 70 $cm^2\ yr^{-1}$.

The three central provenances — Ukiah, Navarro River, and Napa — exhibited fairly similar average yearly basal area increments, ranging from approximately 31 to 40 $cm^2\ yr^{-1}$, with median values between 30 and 35 $cm^2\ yr^{-1}$.

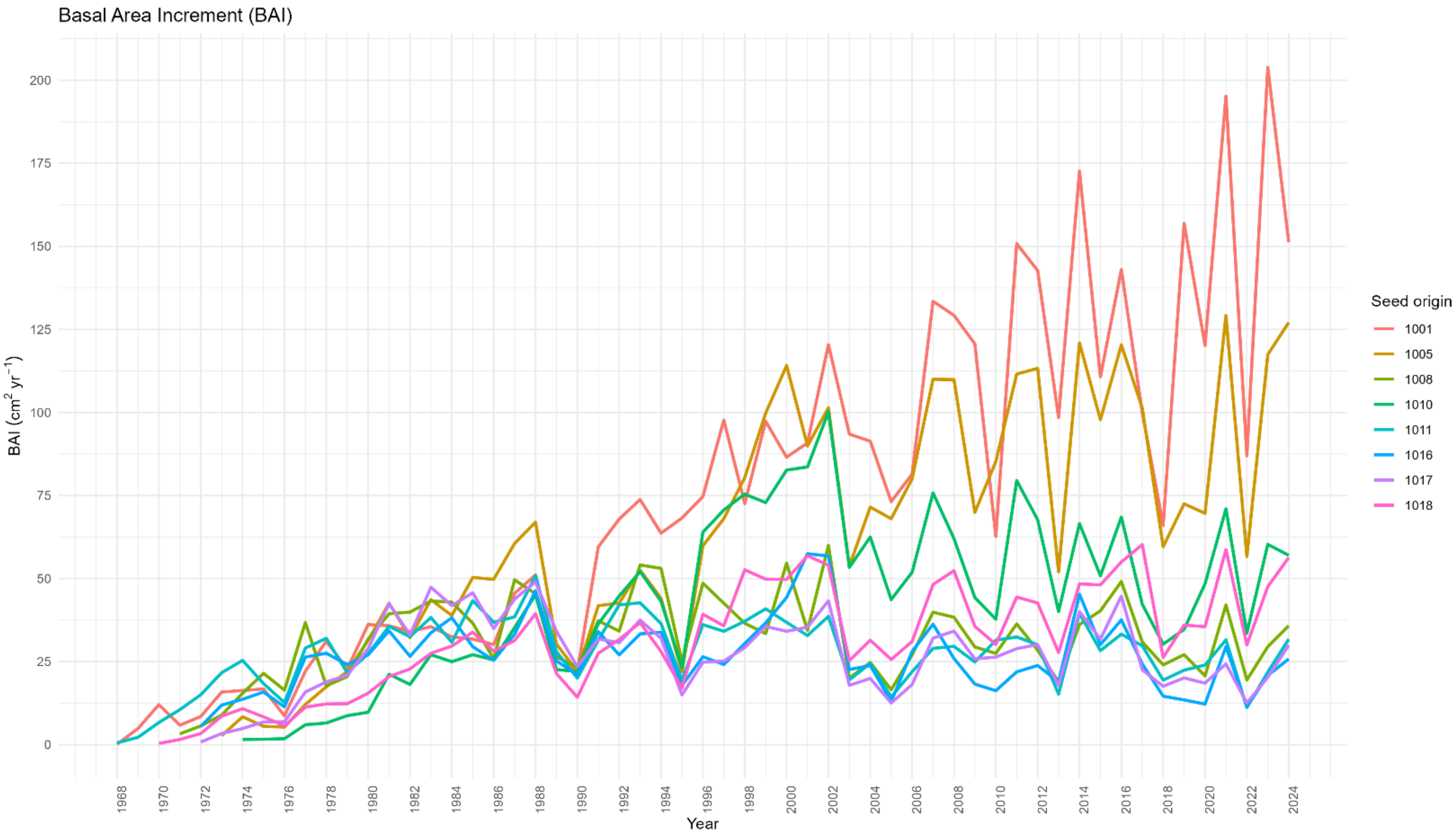

Figure 11 - Mean Basal Area Increment (BAI) for all seed origins from 1968 to 2024, expressed in cm^2 yr^{-1}.

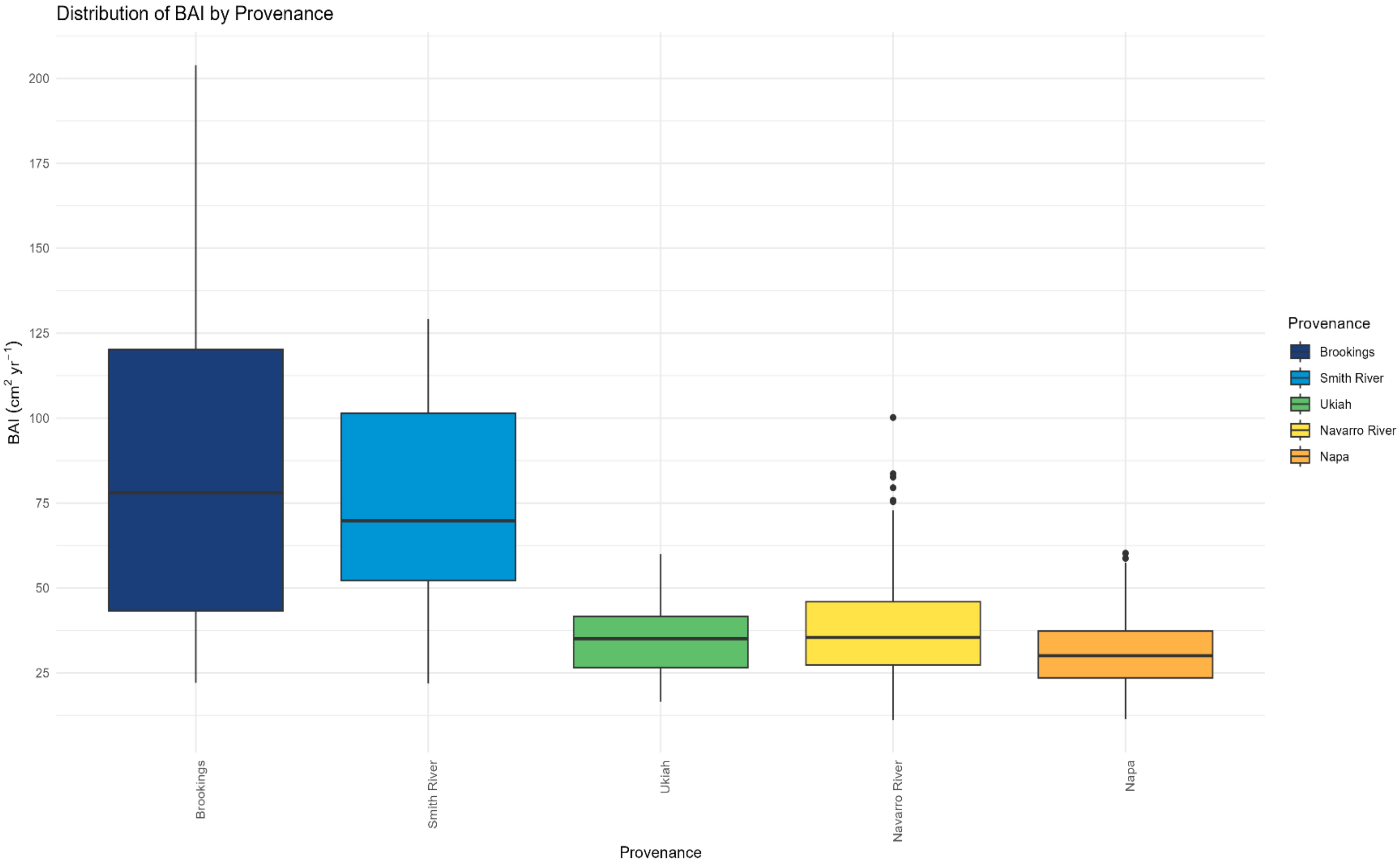

Figure 12 – Distribution of annual average basal area per provenance from 1968 to 2024, expressed in $cm^2\ yr^{-1}$.

4.4.4 Climate data

There is an increasing trend in temperature (Figure 13), while precipitation has remained relatively stable at Alice Holt (Figure 14). Since 1965, the mean temperature has risen by nearly 1.5 °C. Mean temperature in all calendar months has increased over the 59-year period from 1965 to 2022, (Figure 15). Monthly precipitation has been very variable (Figure 16) and for several of the months shows no overall trend during the same period, although April, May, and September have declined, while October showed the largest increase.

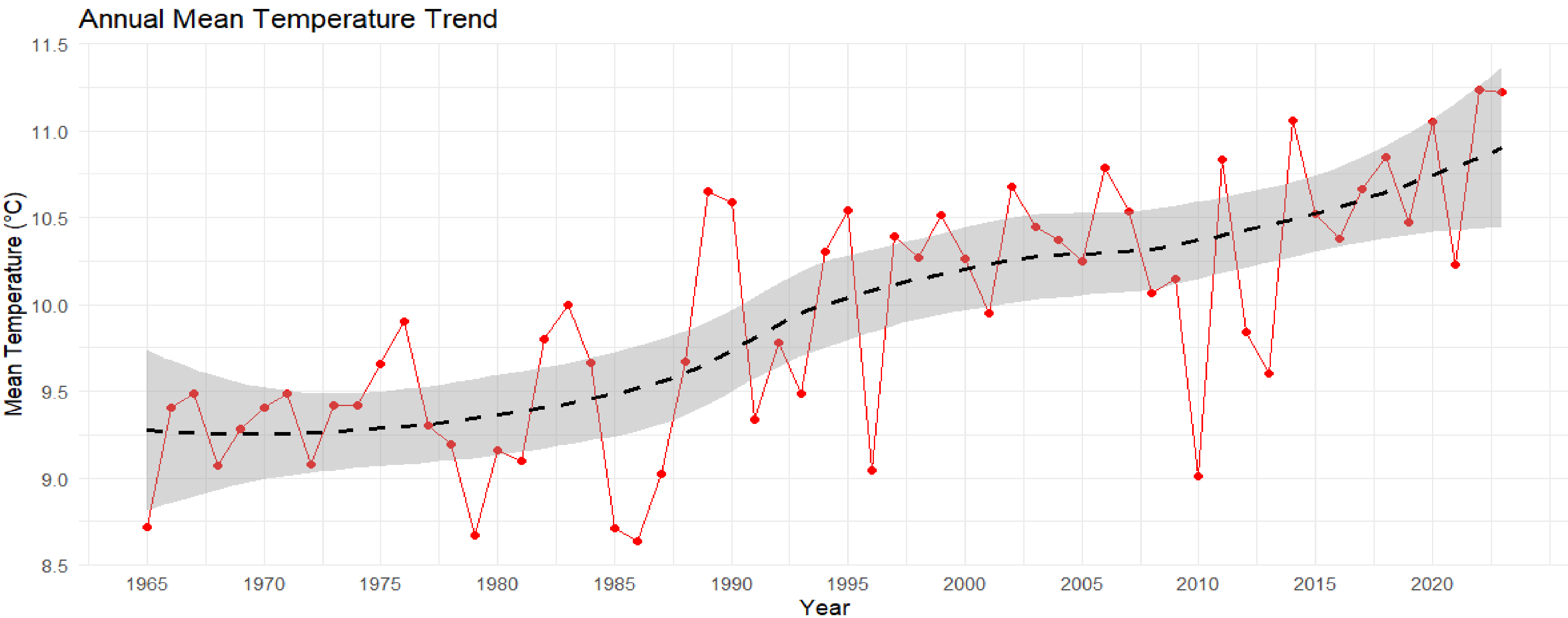

Figure 13 - Annual mean temperature trend from 1965 to 2022. Red points represent yearly mean temperatures, while the black dashed line shows the smoothed trend with a 95% confidence interval (grey shading).

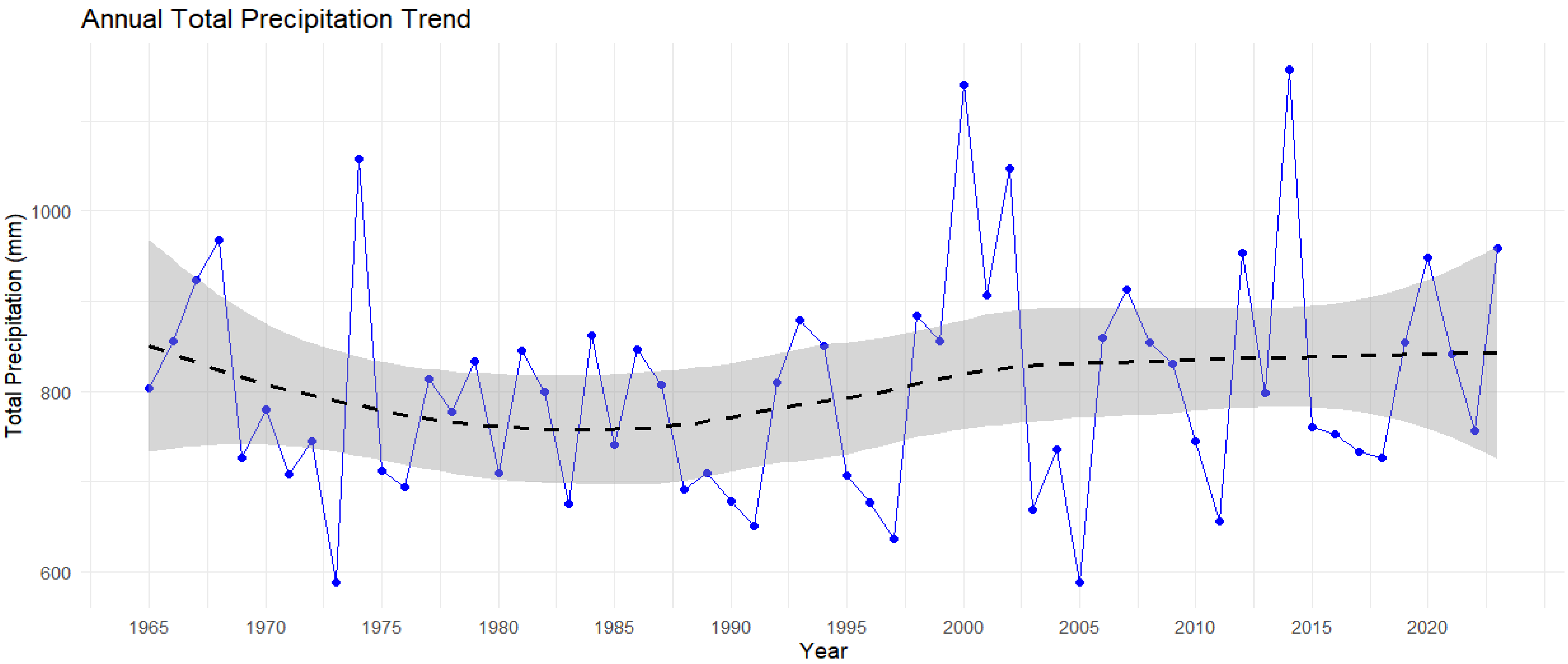

Figure 14 - Annual total precipitation trend from 1965 to 2022. Blue points and lines represent yearly total precipitation, while the black dashed line shows the smoothed trend with a 95% confidence interval (grey shading).

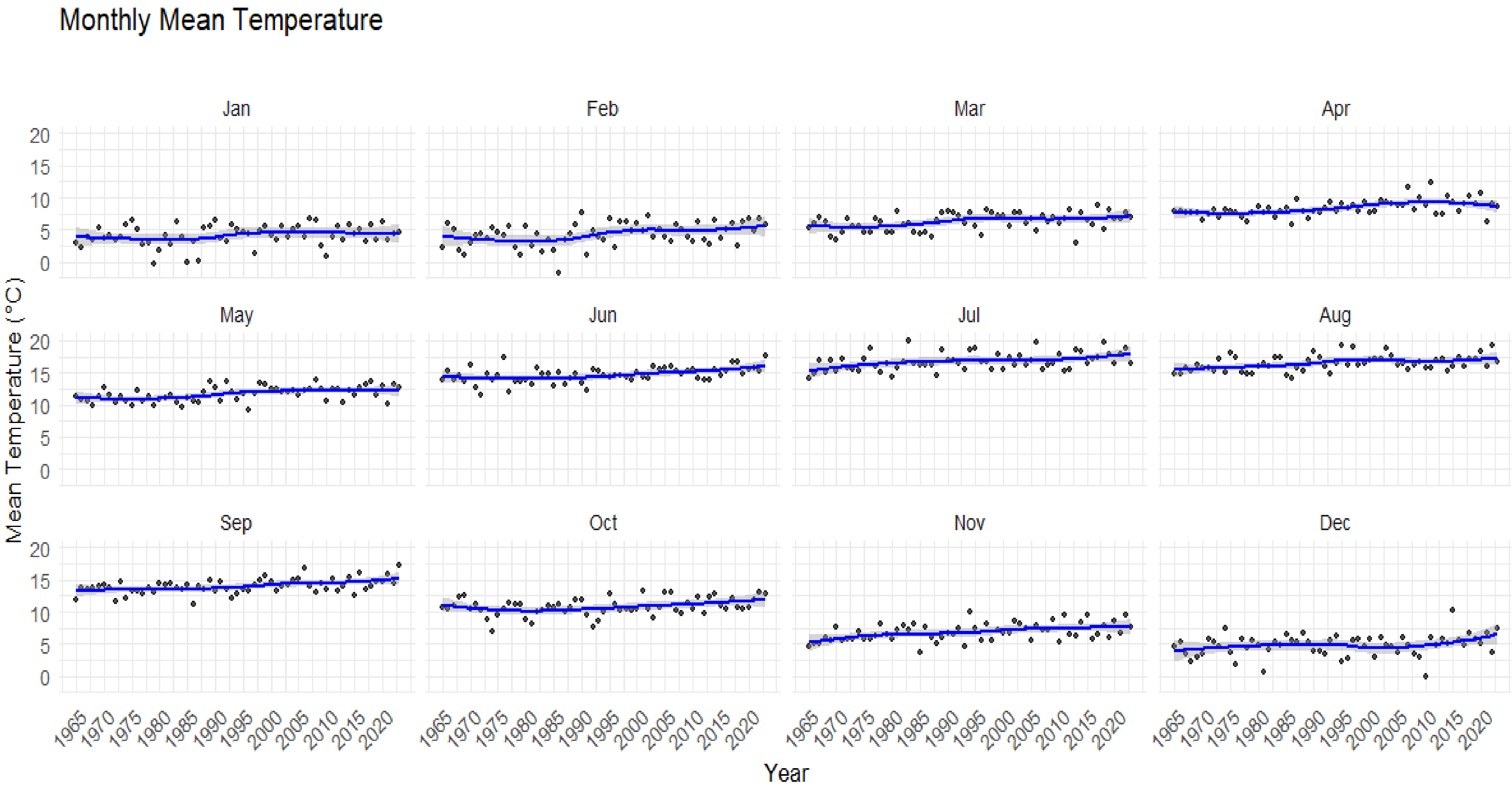

Figure 15 - Monthly mean temperature trends at Alice Holt from 1980 to 2020. Each panel represents a separate month (black points) and trend lines (blue) over time.

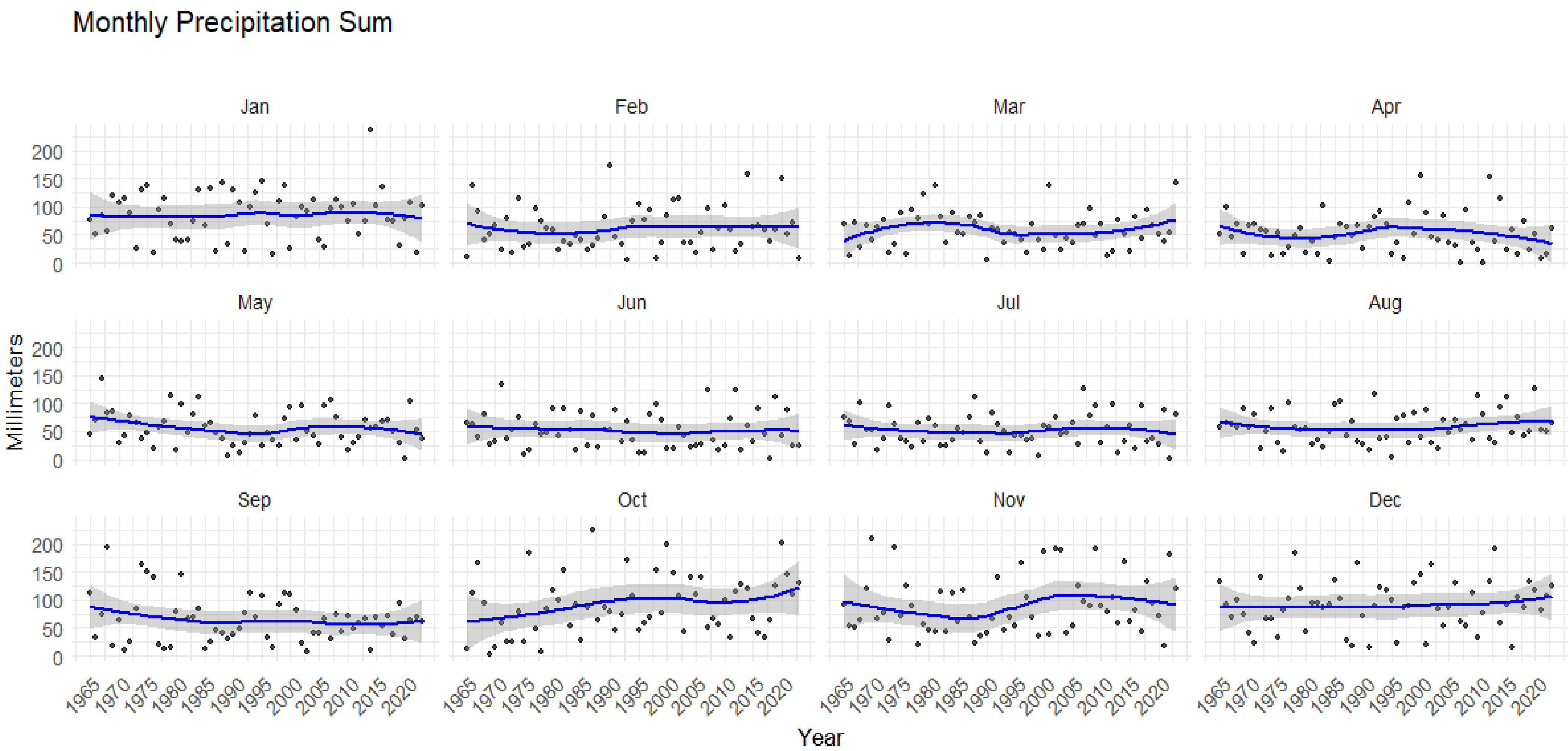

Figure 16 - Monthly precipitation sums from 1980 to 2020. Each panel displays precipitation totals for a given month (black points), with a blue trend line indicating long-term patterns.

4.4.4.1 Drought Events

Figure 17 shows SPEI calculated with a 6-month time scale, from March to August, and we chose two categories to differentiate extreme from severe droughts. A SPEI value of -2 to -1.5 is classified as severe drought and values ≤ -2 as extreme drought events.

The SPEI values for the periods from April to September showed that 1976 and 1997 were classified as extreme drought while 1989, 1990, 1992, 1995, 2003, 2005, 2011, 2017, 2018, 2022 were classified as severe drought (Table 5).

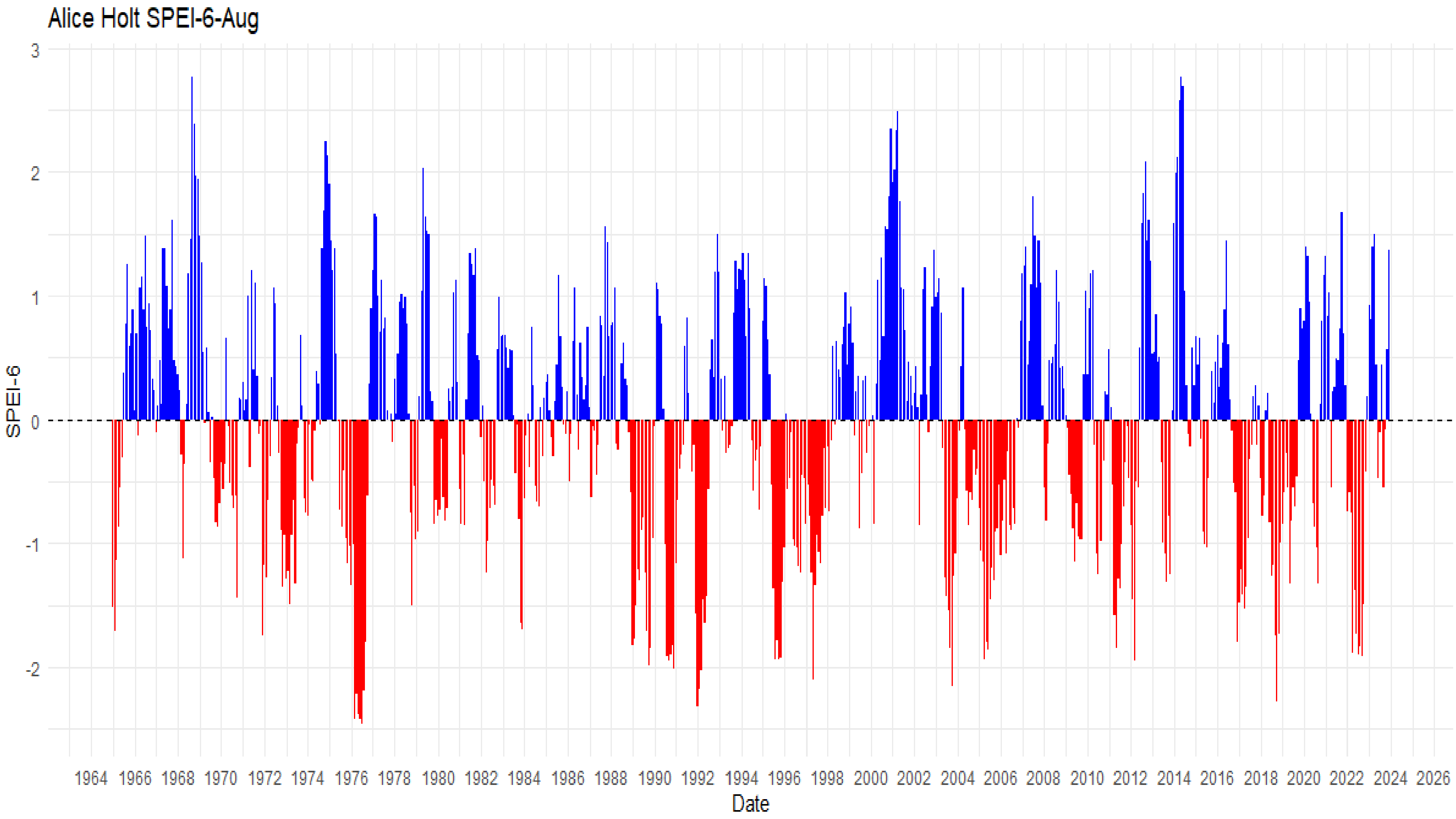

Figure 17 - A graph showing the yearly 6-month SPEI values from 1965-2024 at Alice Holt

Table 6 - Years experiencing *severe* (−1.5 ≤ index < −2.0) or *extreme* (index ≤ −2.0) drought conditions, based on SPEI drought index values for April-September from a grid square value.

Year	Value	Degree
1976	-2.46	Extreme
1989	-1.71	Severe
1990	-1.95	Severe
1992	-1.65	Severe
1995	-1.93	Severe
1997	-2.11	Extreme
2003	-1.85	Severe
2005	-1.94	Severe
2011	-1.85	Severe
2017	-1.53	Severe
2018	-1.74	Severe
2022	-1.91	Severe

To explore the relationship between tree growth and drought conditions, Figure 18 displays temporal trends in standardized tree growth alongside drought severity, allowing for visual assessment of climate-growth relationships across provenances. Figure 18 highlights how severe drought periods such as 2005, 2017, 2018, and 2022 align well with reductions in growth. In contrast, 1989 shows a delayed response, with growth dropping in 1990. Interestingly, the extreme 1997 drought does not correspond with a sharp decline in growth; instead, growth appears to have decreased more significantly during the earlier severe 1995 drought and then recovered before. It’s unclear why growth didn’t decrease further during a more severe drought—this could reflect species-specific physiological responses, the influence of other environmental factors, or limitations in using the 6-month SPEI as a drought metric in this context.

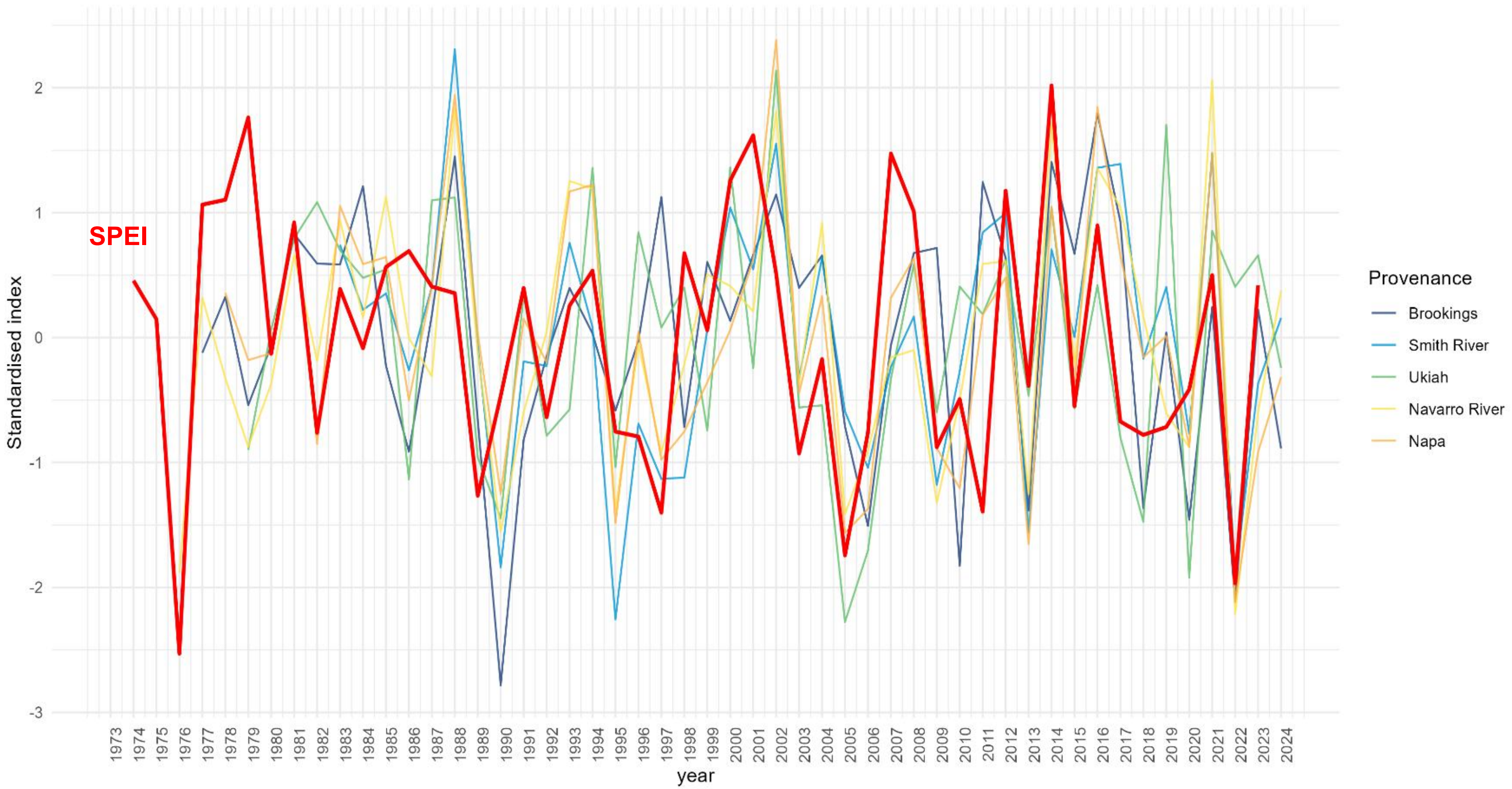

Figure 18 - Time series of standardized ring width indices (RWI) and growing season drought index (SPEI) from 1973 onward. Coloured lines represent z-scored RWI values for individual coast redwood seed origins, while the red line shows the z-scored SPEI averaged across April–September. Both indices are standardized to facilitate direct comparison.

4.4.5 Climate-Growth Relationship

To explore the relationship between climate and radial growth, we conducted both static and moving correlation analyses. Static correlations assess the influence of monthly climate variables within fixed time windows, while moving correlations allow for the detection of temporal shifts in climate-growth relationships over time. Due to the nature of growth patterns in the RWI and BAI analyses of the two northernmost provenances, Brookings and Smith River, they were excluded from this analysis to avoid edge effects that may confound interpretation. All static and moving correlation results for each provenance are provided in Appendix D.

4.4.5.1 Static Correlations

All three provenances in Appendix D showed negative correlations between RWI and late summer to early autumn temperatures. Notably, Navarro River and Napa exhibited statistically significant negative correlation coefficients during July and August, with values of approximately -0.38 and -0.43 for Navarro River, and -0.40 and -0.49 for Napa. Additionally, October temperatures at Navarro River also showed a significant negative correlation with RWI, with a coefficient of -0.38. These findings suggest that higher temperatures during late summer and early autumn tend to limit radial growth across provenances, contrary to expectations that warmer conditions would extend growth. This likely reflects the compounding effects of seasonal drought and heat stress, which can suppress growth despite elevated temperatures.

Precipitation influenced radial growth across the RSQ provenances, with all three provenances exhibiting significant positive correlations between RWI and monthly precipitation totals, particularly during late spring and summer of the current growth year, indicating sensitivity to moisture availability during the main growing season. All three provenances—Ukiah, Navarro River, and Napa—showed significant relationships between RWI and precipitation during May and June, with correlation coefficients of 0.28, 0.30, and 0.37 for May, and 0.35, 0.36, and 0.38 for June, respectively. Additionally, Navarro River and Napa exhibited significant positive correlations for July, with coefficients of 0.37 and 0.42, respectively. These results indicate that moisture availability during key stages of the growing season plays a significant role in tree growth.

It can also be noted that Navarro River and Napa followed quite similar static precipitation and temperature correlations, with overlapping significant months and comparable coefficient values. This similarity is notable given their geographic separation, and it might be expected that Ukiah and Navarro River would show greater similarity due to their close latitudinal proximity. These findings highlight the potential value of analysing Ukiah, Navarro River, and Napa collectively as a single latitudinal cluster, given their geographic closeness and the relatively minor variation in climate-growth relationships between Navarro River and Napa.

4.4.5.2 Moving Correlations

The moving correlation analysis (Appendix D) shows that sensitivity of radial growth to monthly temperature shifted over time for RSQ provenances. Since 1991-2010 period, all three provenances have shown increasingly positive correlations with late winter and early spring temperatures, particularly between January and May, suggesting greater sensitivity to early-year warmth. Conversely, July and August temperatures have persistently exerted negative effects on growth across provenances since the early 1970s, additional negative responses to June temperatures were noted. These results highlight a trend of increased growth responsiveness to warm conditions in late winter and early spring, alongside persistent negative impacts from elevated summer temperatures, likely due to heat and drought stress during the main growing period.

The moving correlation analysis revealed that total monthly precipitation had a measurable influence on radial growth across provenances, with some sites showing consistent sensitivity to specific months and others exhibiting shifts or emerging patterns over time. Across provenances, tree growth generally showed strengthened positive associations with spring and early summer precipitation in recent decades, particularly from April to July. Precipitation from late summer and early autumn of the previously year, especially August and September, also exerted a continuing positive influence on growth, indicating the lasting importance of residual moisture available from the preceding growing season. These findings suggest that moisture during spring and early summer plays a vital role in determining radial growth.

The moving correlation analysis between RWI and the Standardised Precipitation-Evapotranspiration Index (SPEI) showed consistent and significant positive relationships across all provenances, particularly during summer and early autumn months. These correlations highlight a shared reliance on adequate moisture available during the late growing season and a sensitivity to drought stress. All 3 provenances exhibited broadly similar positive correlations from June to October across the whole time period and also revealed emerging positive influences at the beginning of the current year (Jan-May) since the 1994-2013 period. This shift was accompanied by a decline in the significance of SPEI values from the previous late summer and autumn (August to December), which had previously contributed positively to growth. These changes may reflect shifts in growing season dynamics, such as earlier onset of cambial activity or altered physiological responses to seasonal water balance under changing climate conditions. Overall, these results underscore the central role of summer and early autumn moisture balance in governing annual growth, with consistent responses across provenances indicating a collective vulnerability to water stress during key growth phases.

5 Conclusions

This pilot study aimed to assess the survival, and bark thickness of various coast redwood provenances at a southern UK trial site, while also exploring the influence of climatic variables on growth through dendrochronological analysis. As there is limited published research on coast redwood performance in the UK, including that of different provenances, this study builds on existing knowledge and begins to highlight how climate variability (1965-2024) has influenced survival and growth responses—providing insights that may help anticipate future climate-related impacts.

Our findings suggest that the first seven years post-planting are critical for establishment and long-term survival in the 7 provenances assessed. Mid-range provenances, Navarro River and Napa, showed survival rates around 50%, performing nearly as well as, or even better than, the most northern provenance, Brookings. In contrast, the southernmost provenances, Mt Mars and Gorda, showed the lowest survival, potentially due to frost sensitivity and limited adaptability to the UK's cooler climate. While the number and severity of spring frosts have generally declined since the 1960s, future vulnerability will likely depend on the timing of bud burst under changing climate conditions.

While frost resistance is likely a key factor, we were unable to directly assess its impact due to a lack of phenological data—specifically, the timing of budburst, which is essential for identifying periods of frost vulnerability. Even with this data, isolating frost as the primary cause of mortality from the historic trial information would remain challenging due to confounding factors such as weed competition, herbivory, and drought stress.

The bark thickness analysis of 9 trees showed that bark decreased with height up the tree. However, bark thickness varied both within and between trees at equivalent height intervals. This variability, combined with a limited sample size, limits the strength of our conclusions. Future research could explore the chemical composition of bark—particularly resin, tannin, and moisture content—to better understand the fire resistance of different provenances.

The statistical analysis confirmed the reliability of the coast redwood chronologies developed for each provenance. All provenances exhibited acceptable levels of mean sensitivity and series intercorrelation, indicating consistent year-to-year growth variability and a shared response to environmental conditions. EPS values met or closely approached the critical threshold of 0.85, supporting the statistical validity of the chronologies. Collectively, these results demonstrate that the dataset is suitable for dendrochronological analysis and could be used to investigate provenance-specific growth patterns and environmental responses in coast redwood.
Mid-latitude provenances maintained stable, moderate BAI growth rates, suggesting good adaptation to site conditions. In contrast, the two most northern provenances showed notably higher productivity, which might be due to the edge effect of an adjacent bridleway and drainage ditch which contribute greater space, light and water availability to these provenances. To better understand these differences, it would be valuable to compare the central provenances with the northern ones using data from replicated trials where provenance locations are randomized. This would allow for a more direct comparison of growth performance, helping to account for potential biases.

Radial growth of the coast redwood provenances exhibited provenance responses to climatic variables, with both temporal changes (over the 60 years stand age) and seasonal variability. The relationships between RWI chronologies and monthly mean temperature and precipitation differed among provenances. Temperature influenced growth in distinct ways. Most provenances showed a consistent negative response to summer temperatures (July and August), suggesting vulnerability to heat stress during the peak growing season. In contrast, temperatures in late winter and early spring (January to May) became increasingly important drivers of growth in recent decades, particularly February.

Precipitation was also a key driver of growth, with positive correlations observed across many provenances during late spring and summer. The timing and strength of these relationships varied, with some provenances exhibiting consistent responses while others showed more complex or shifting patterns over time. Precipitation from the previous growing season (particularly in August and September) also appeared to have a positive effect in several provenances.

Moving correlation analysis further revealed change over time in climate–growth relationships. The analysis of an index of moisture demand (the standardised precipitation index, SPEI) over the April-September period underscored the critical importance of summer and early autumn water balance for radial growth across all provenances. Strong and sustained positive correlations with SPEI from June to October suggest that moisture stress during this period constrains growth, and that many of the RSQ provenances examined here may be increasingly vulnerable under future climate scenarios with hotter and drier summers.

Overall, these findings illustrate the complex and dynamic interactions between key climate variables and past tree growth in coast redwood grown in southern England. The single trial results, although necessarily limited, suggest there is a need to consider provenance, when evaluating forest resilience, selecting planting material, or planning adaptive management strategies under changing climatic conditions.

This pilot study provides a foundation for future research. With two additional replicated trials of coast redwood, using similar seed origins established in other counties of SE England in the 1960’s and not yet assessed, there is strong potential to expand our understanding of provenance-specific responses. Although only four provenances are shared across all three sites, meaningful comparisons—both direct and latitudinal—could still be made, provided survival rates are sufficient.

A deeper understanding of coast redwood phenology and native environmental conditions will be essential to interpreting provenance-specific responses. Future research could therefore potentially examine coast redwood drought response using indices of resistance, recovery, and resilience, providing insight into adaptive capacity under changing climate conditions. It would also be beneficial to assess wood density through the blue intensity method to better understand structural properties and potential links to drought performance. As the dataset grows, we could then begin to model current and future growth trajectories using forest growth models such as 3PG, helping to inform long-term management and climate adaptation strategies.

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7 Appendix

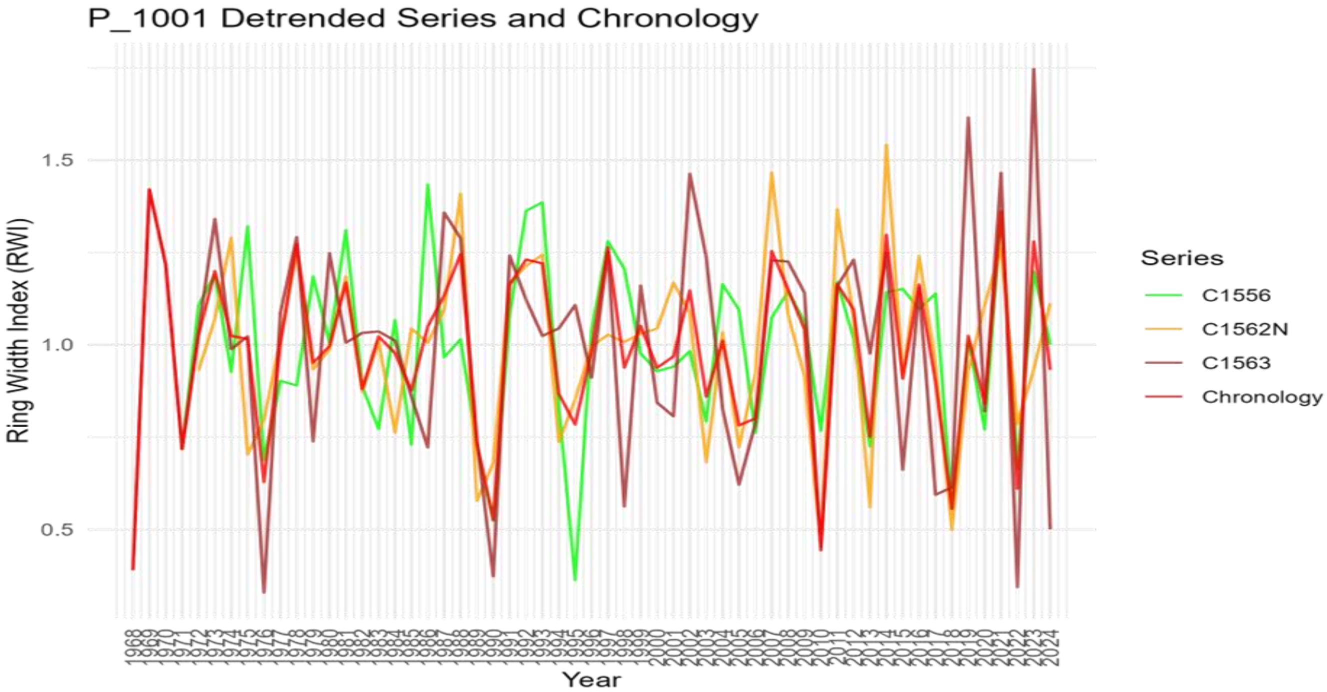
Appendix A – Provenance Site Comparisons

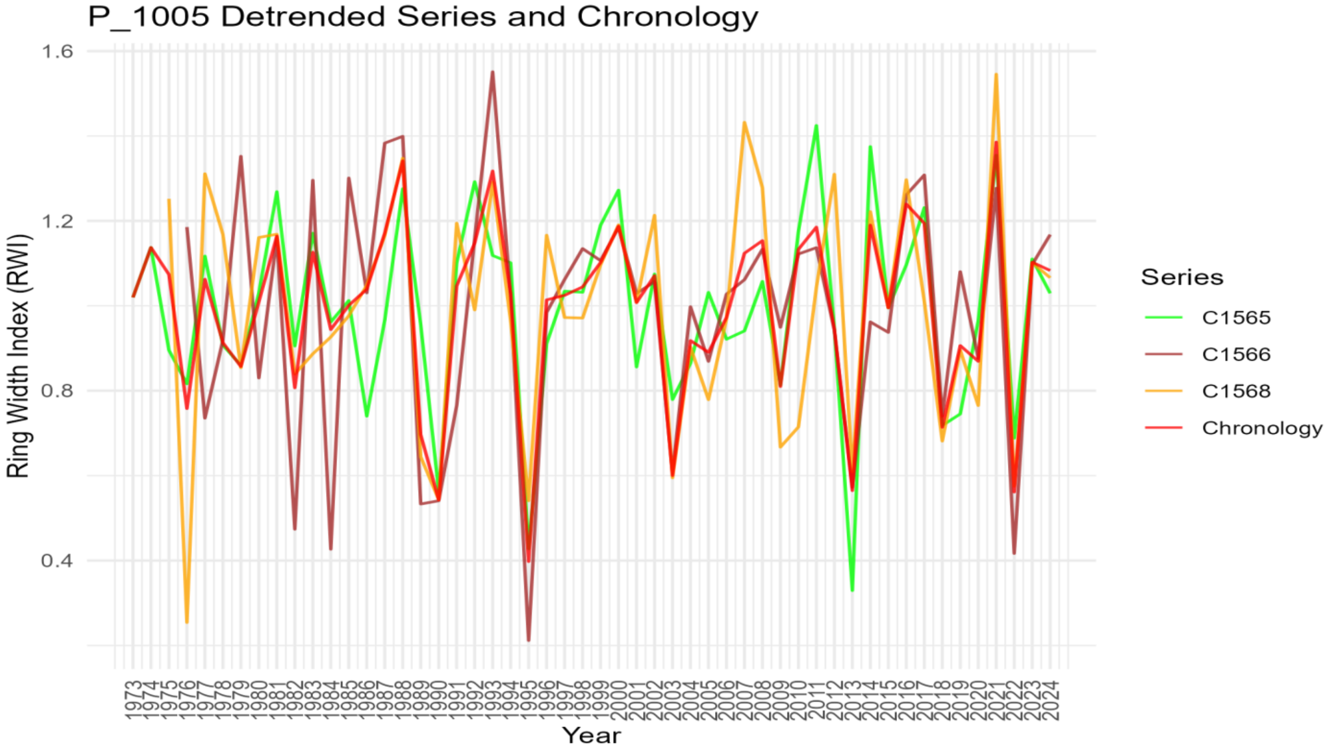
As part of this work, we visited Alton 24 to assess the state of the trial and if it could be possible to make comparisons between the growth and survival of provenances between the other sites. Alton 24 is a randomised block with 9 different provenances replicated 3 times across the site (except for provenance 1018 which was only replicated twice). Each provenance block was spaced at 5ft x 5ft with trees in a 3 x 3 sequence at a planting spacing of 2.5ft. It is an impressive stand with ~48 trees remain which have a great form and stand very straight, likely to be greater than 25m tall and have DBHs of greater than 50cm. There was also clear evidence of thinning with advanced natural regen apparent throughout, with many coppiced redwoods sprouting up from old stumps. We were able to begin to determine where the provenances stood due to a few old post markers remaining and began marking up which trees were living, missing/dead, or coppiced, and so determine that it is possible to reestablish the old plot markings. However, in total only 4 provenances matched up and were directly comparable to those in AH 147 (Table 1).

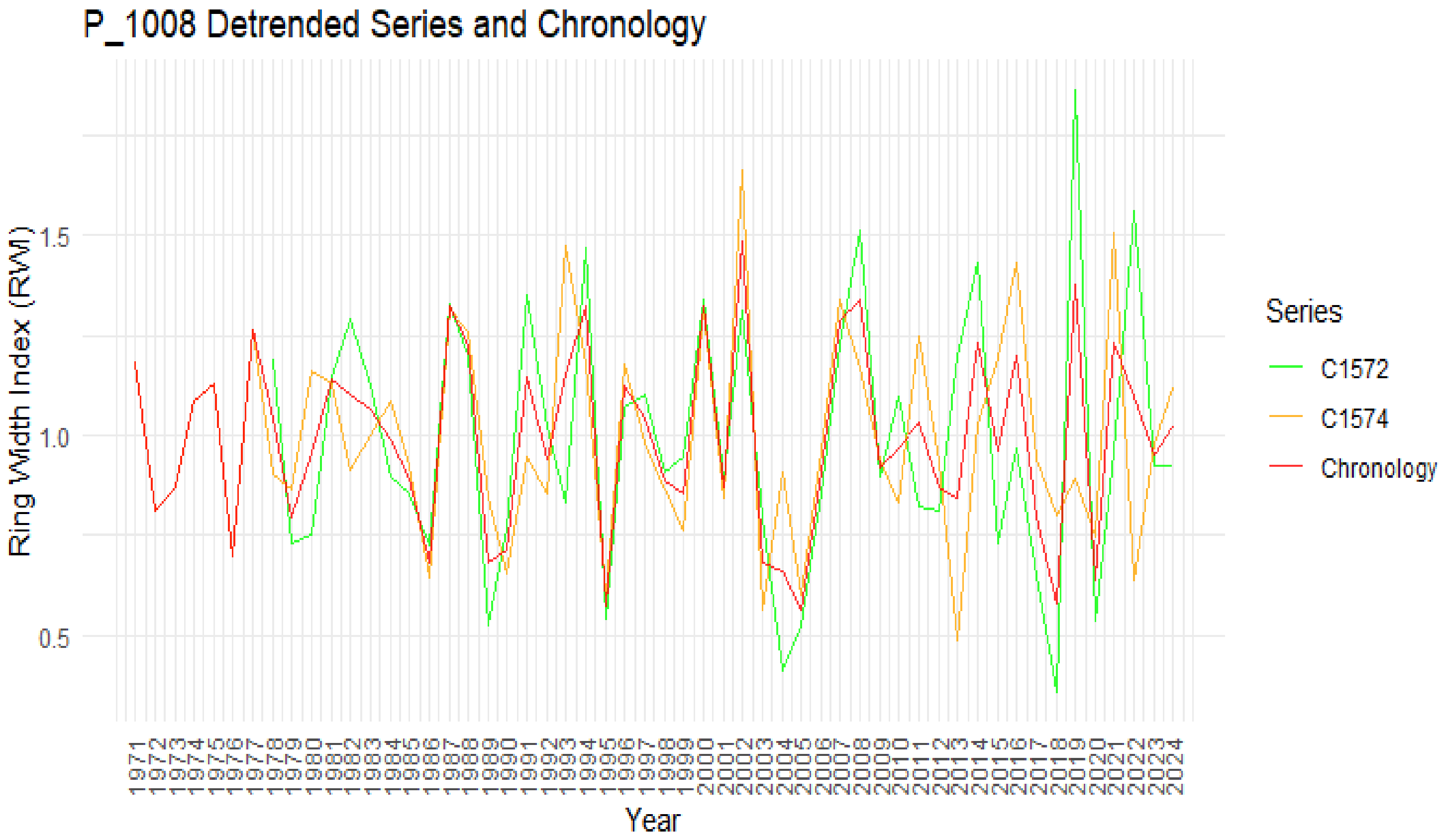
Additionally, the old documents and field visit notes from past visits to Plym 3 outlined how 11 different provenances were planted on a slope in a randomised block formation with each provenance replicated 3 times across the site. Each provenance block was spaced at 40’ x 37.5’ with trees planted in a 5 x 5 sequence. Previous field notes from 2019 & 2020 noted that the sequoias had poor growth likely due to under-management, with many trees showing evidence of their tops being blown out with plenty of forking. As of 2020, 164 trees had been recorded with 34 marked up for thinning, with considerations made based on form, provenance and basal area. In total, 5 and 7 provenances could be directly compared to Alton 24 and AH 147 respectively.

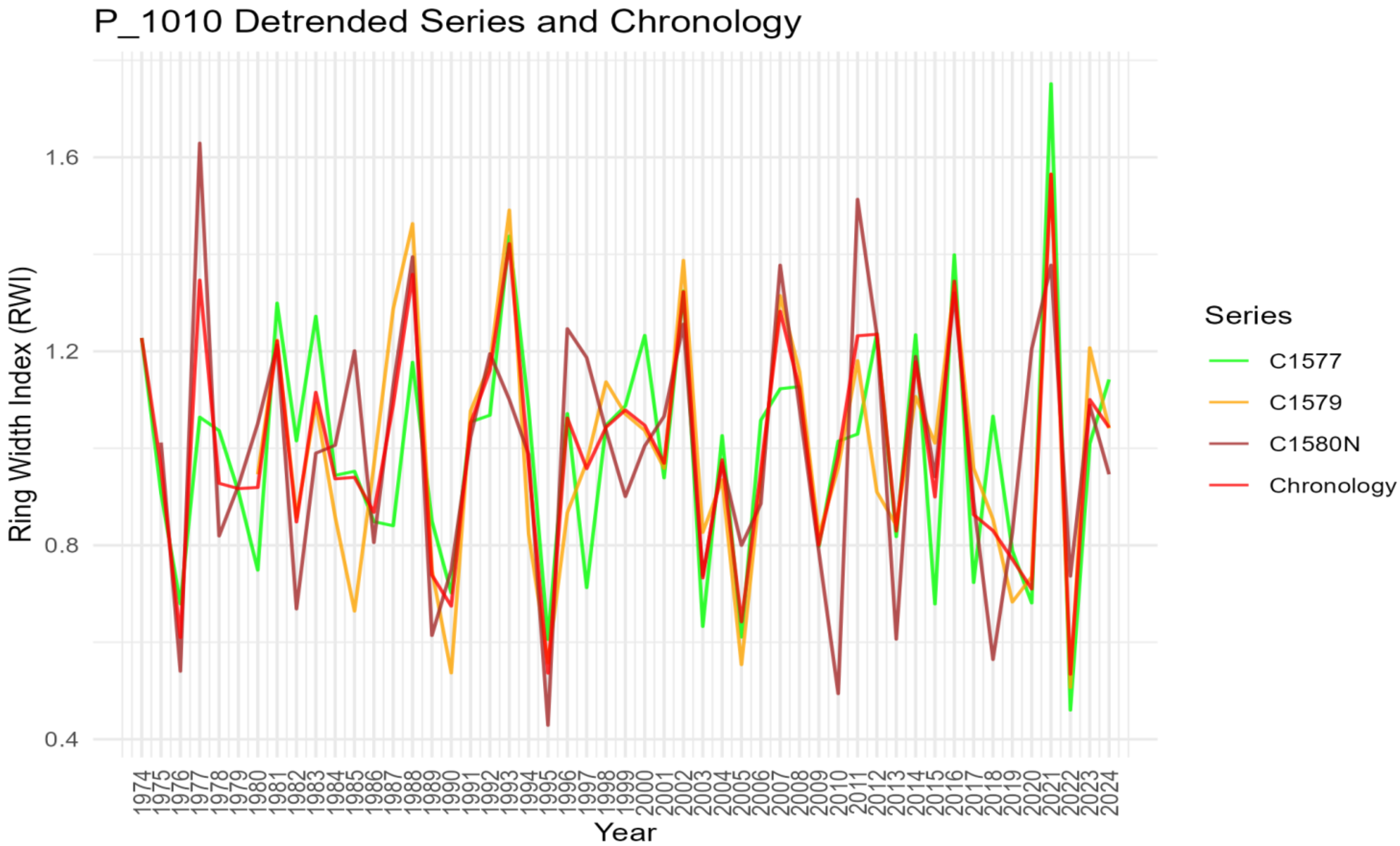
Appendix B – Detrended RWI per Seed Origin

The overall chronology of each seed origin has been overlain against the detrended seed origins in order to visualize and demonstrate the effect and validity of the detrending process.

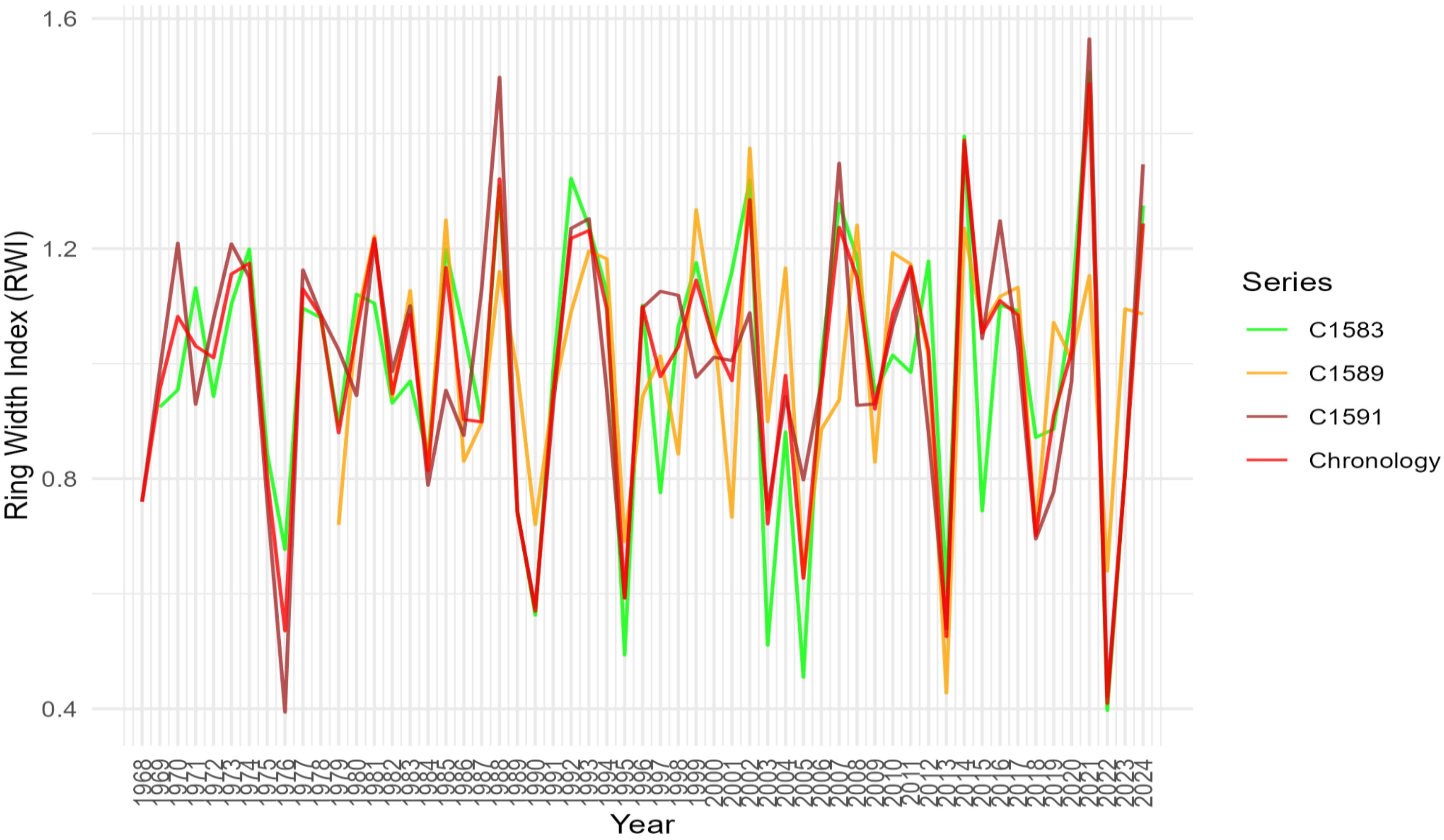




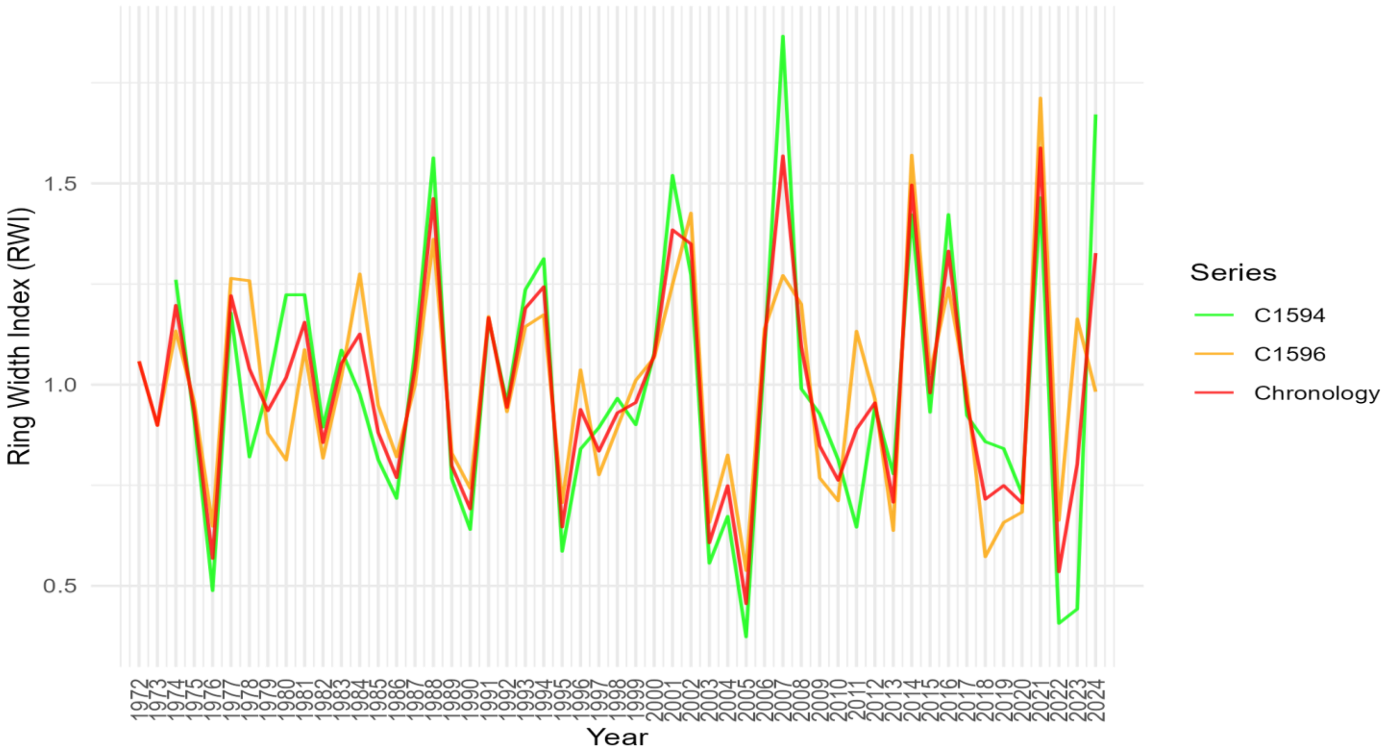

P_1008 Detrended Series and Chronology
Ring Width Index (RWI)
Year
Series
C1572
C1574
Chronology

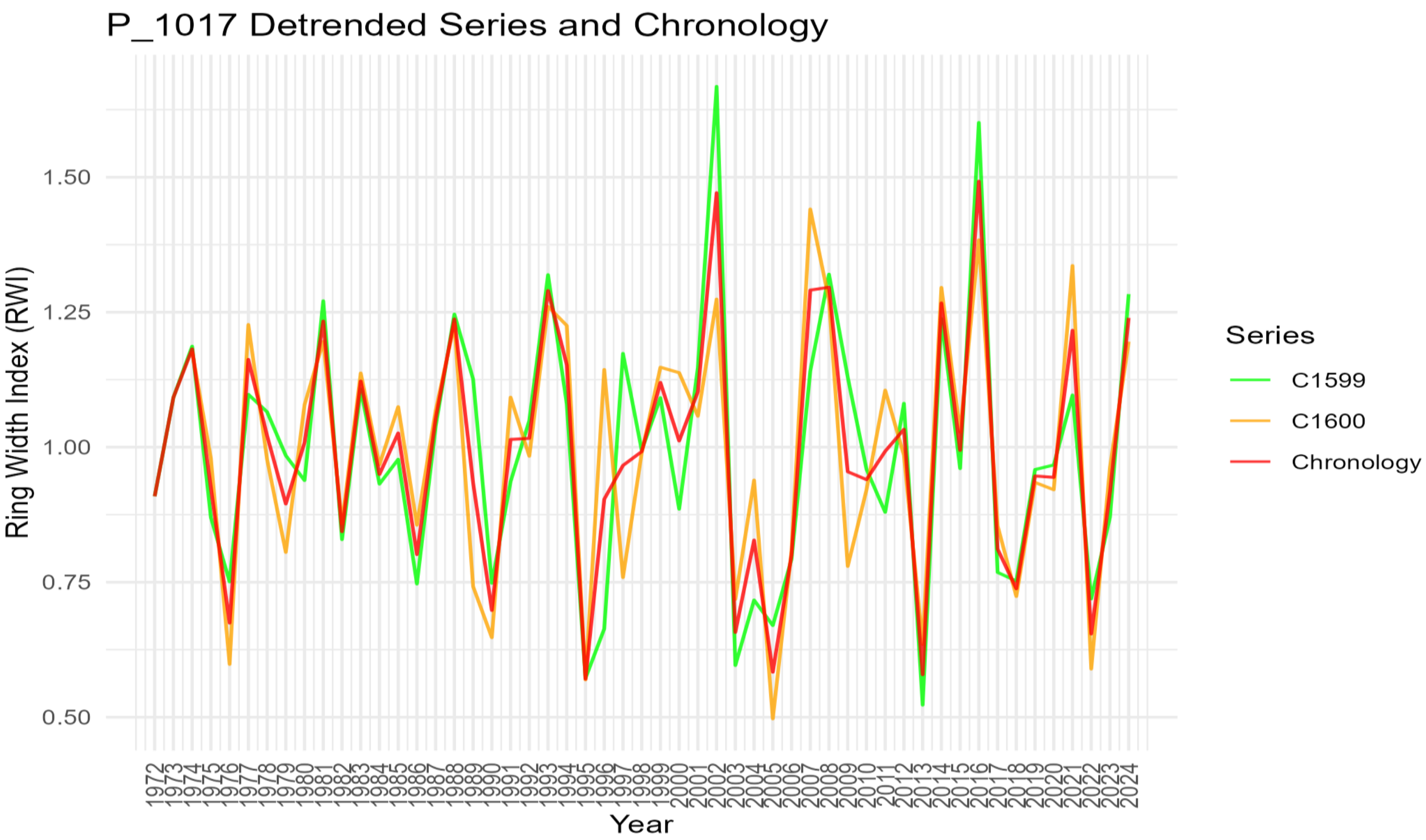

P_1010 Detrended Series and Chronology
Ring Width Index (RWI)
Year
Series
C1577
C1579
C1580N
Chronology

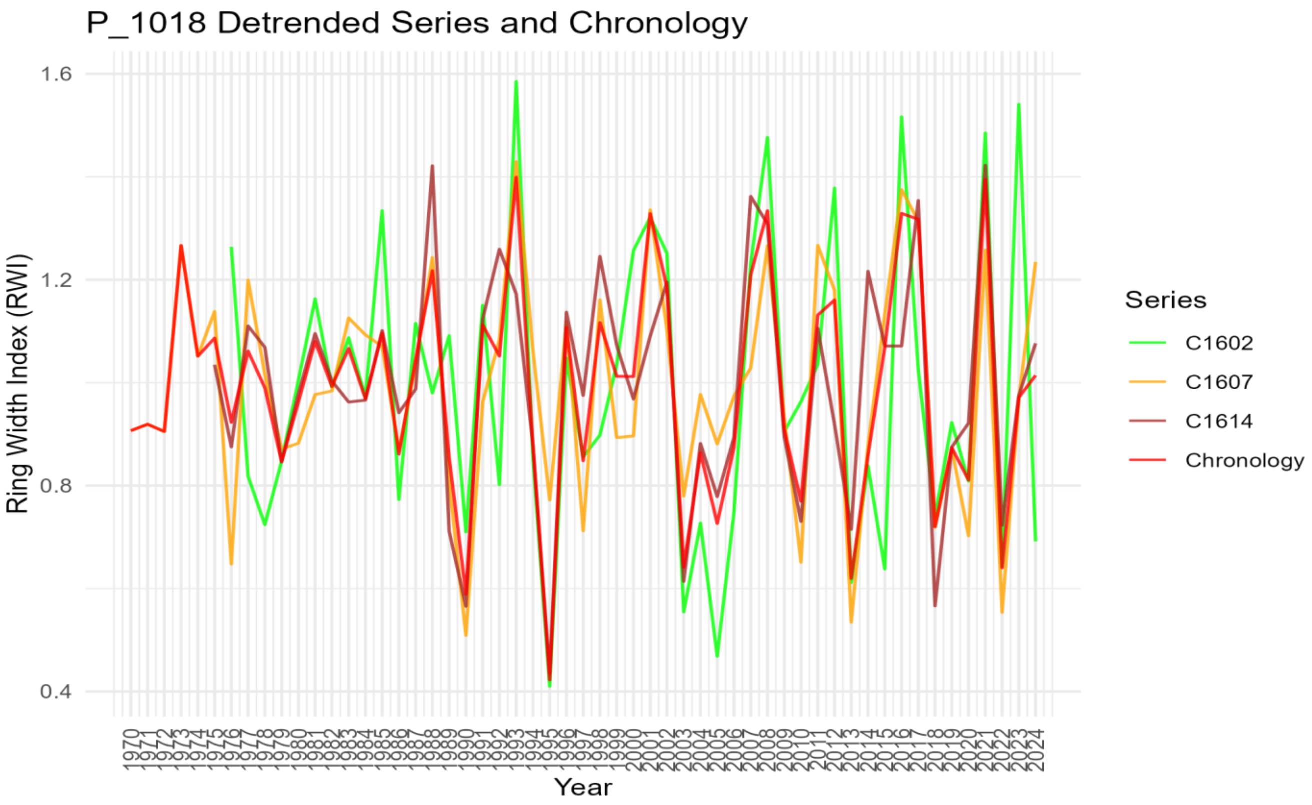
P_1011 Detrended Series and Chronology



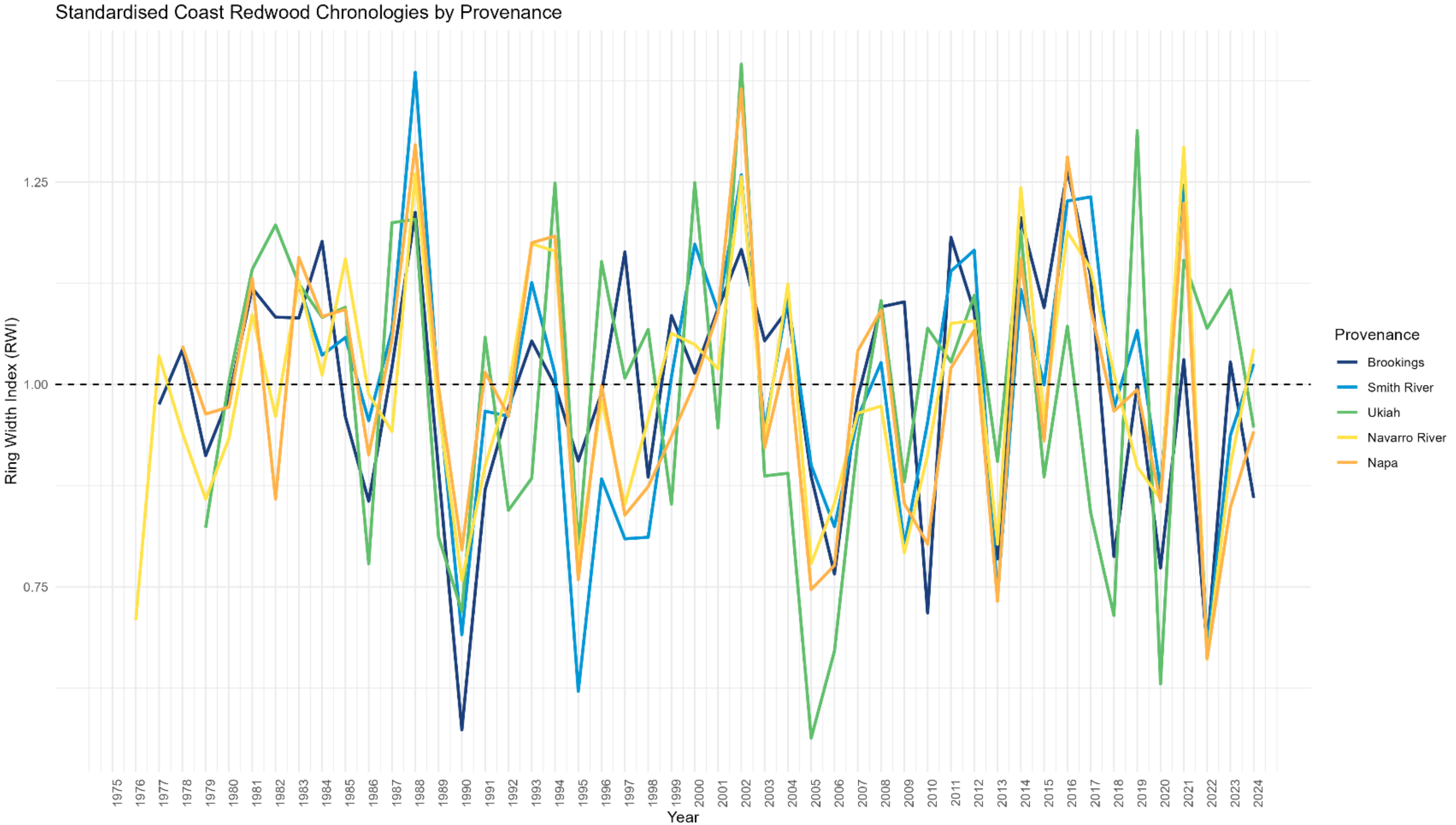
P_1016 Detrended Series and Chronology




P_1017 Detrended Series and Chronology
Ring Width Index (RWI)
Year
Series
C1599
C1600
Chronology


P_1018 Detrended Series and Chronology
Ring Width Index (RWI)
Year
Series
C1602
C1607
C1614
Chronology

Appendix C – RWI per Provenance

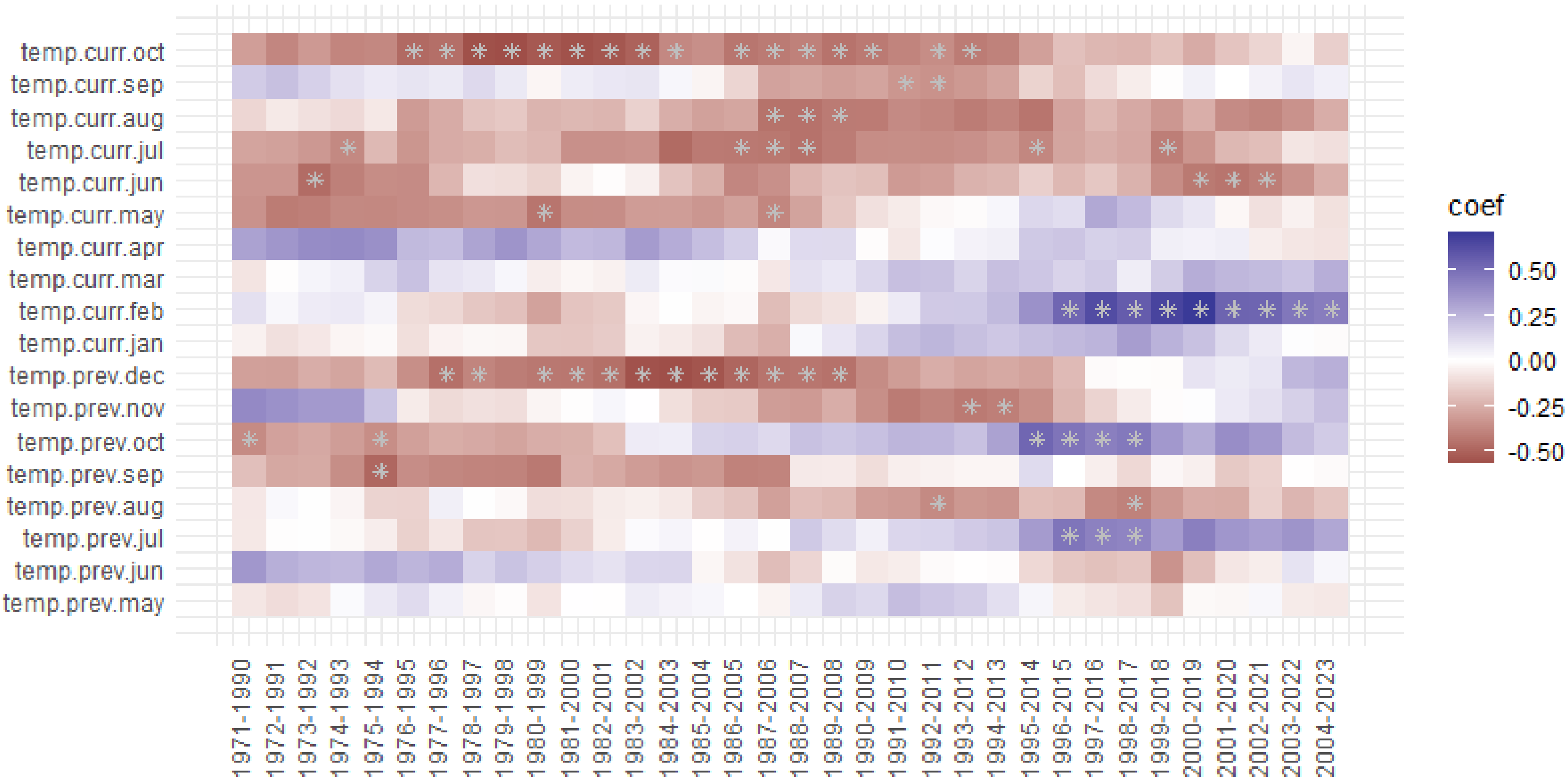


Appendix D – Climate Growth Relationships per Provenance.

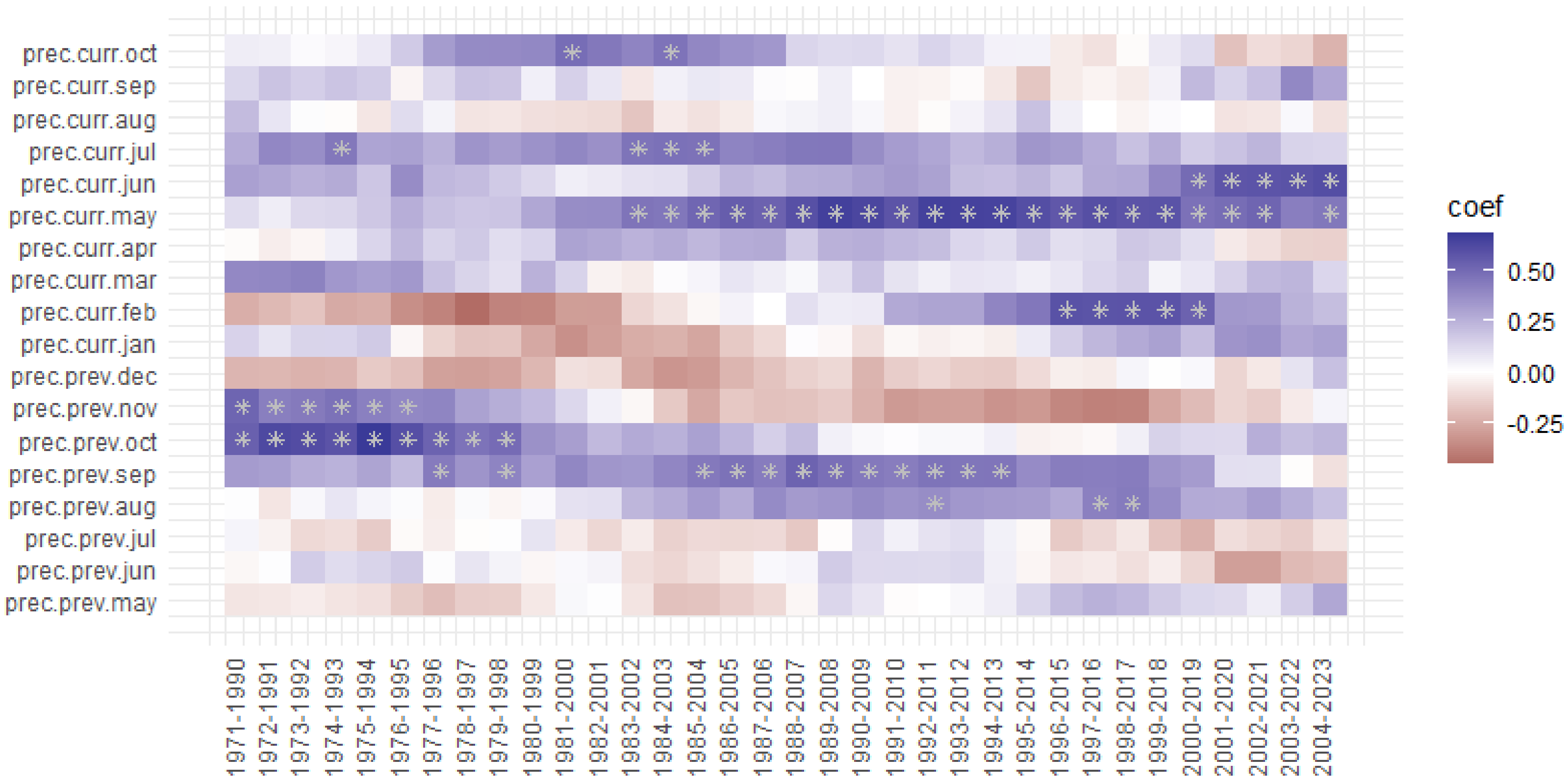
Each panel shows moving-window correlations (20-year window, 1-year step) between RWI and climate predictors (temperature, precipitation and SPEI), with the x-axis indicating the final year of each window, the y-axis showing months/seasons (including previous year “prev” labels), colour indicating correlation magnitude, and overlaid symbols marking significant correlations at $p < 0.05$.

Response function (static) correlation coefficients between monthly climate variables and tree-ring width indices for the study provenances. Panels show correlations with mean monthly temperature (temp), and with total monthly precipitation (prec). Each point represents the correlation coefficient for a given month, with dotted lines indicating non-significant correlations and solid lines indicating statistically significant correlations ($p < 0.05$). Months from the previous growing season are shown in lowercase, and months from the current growing season are shown in uppercase.

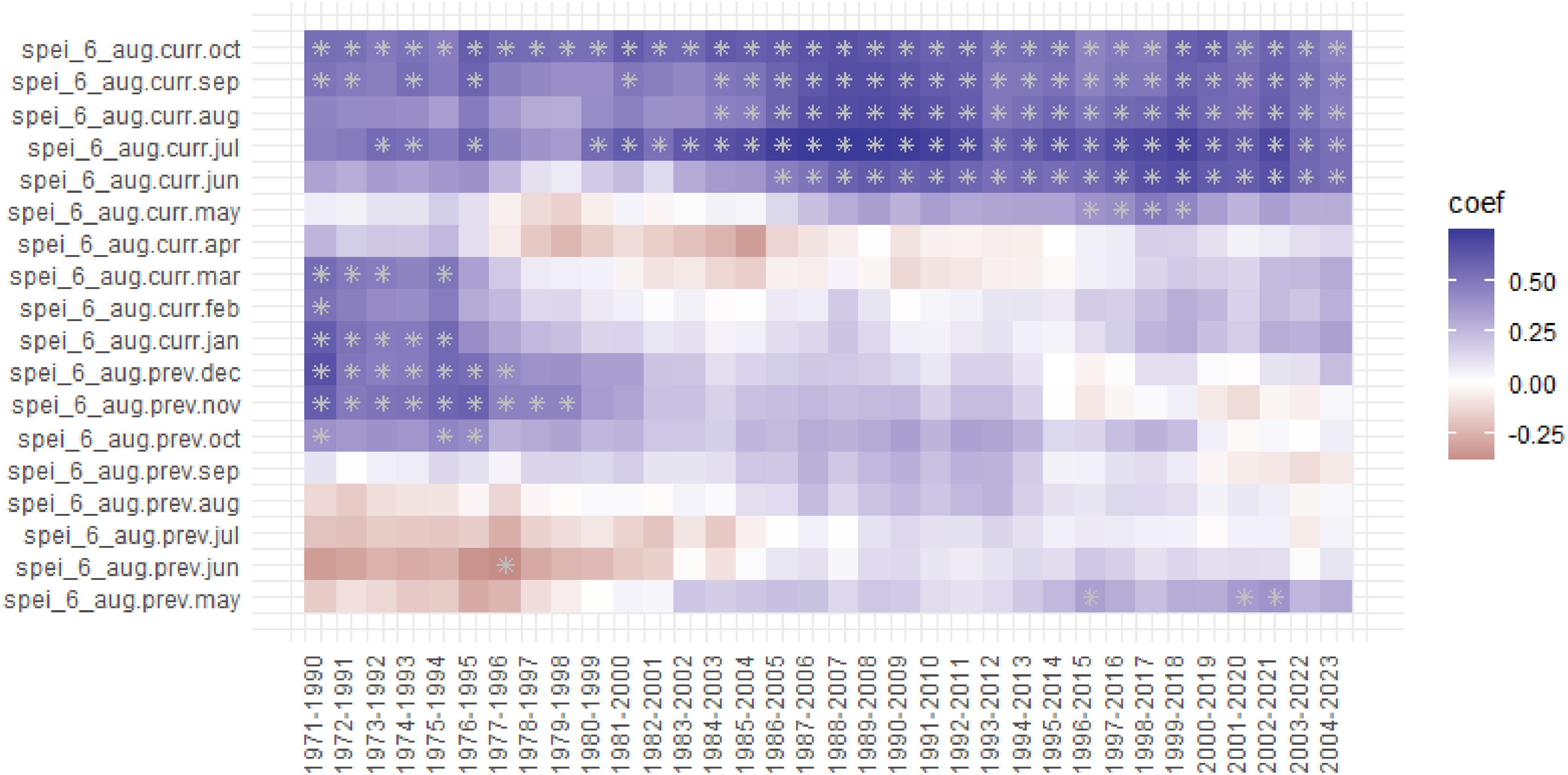
Moving correlation analysis of temperature with RWI in provenance Ukiah (P1008)



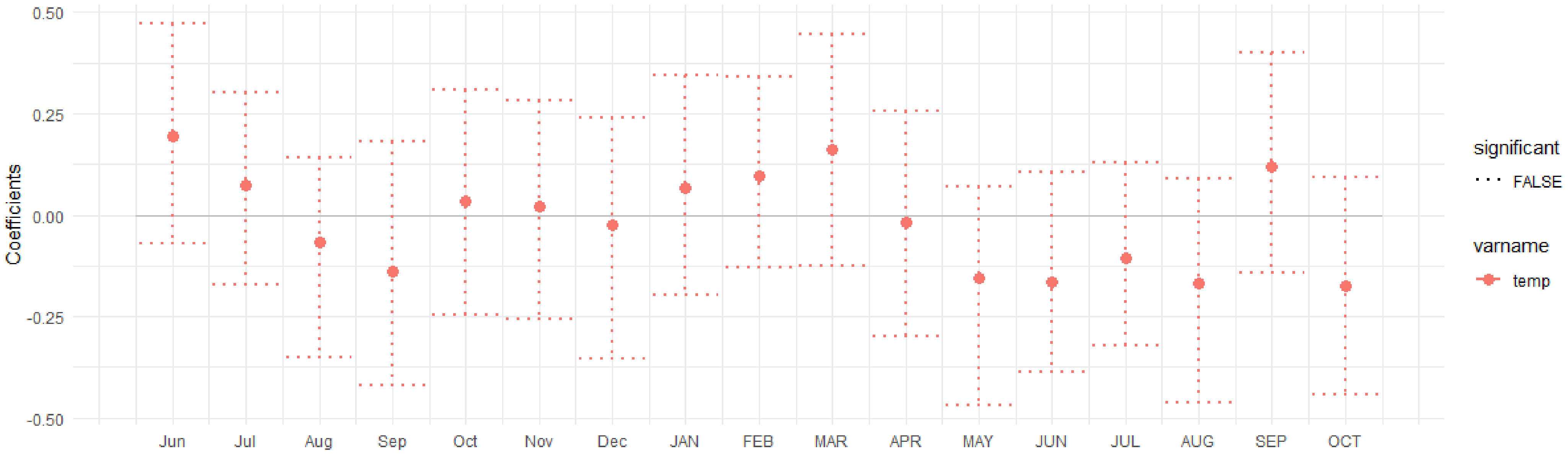
Moving correlation analysis of precipitation with RWI in provenance Ukiah (P1008)



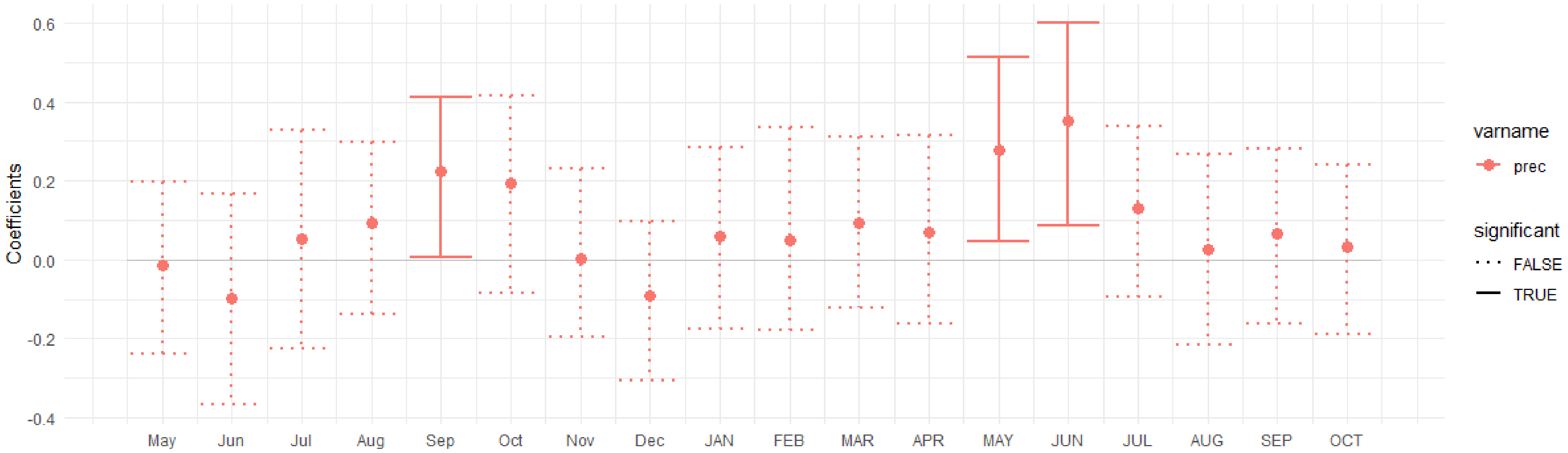
Moving correlation analysis of SPEI with RWI in provenance Ukiah (P1008)



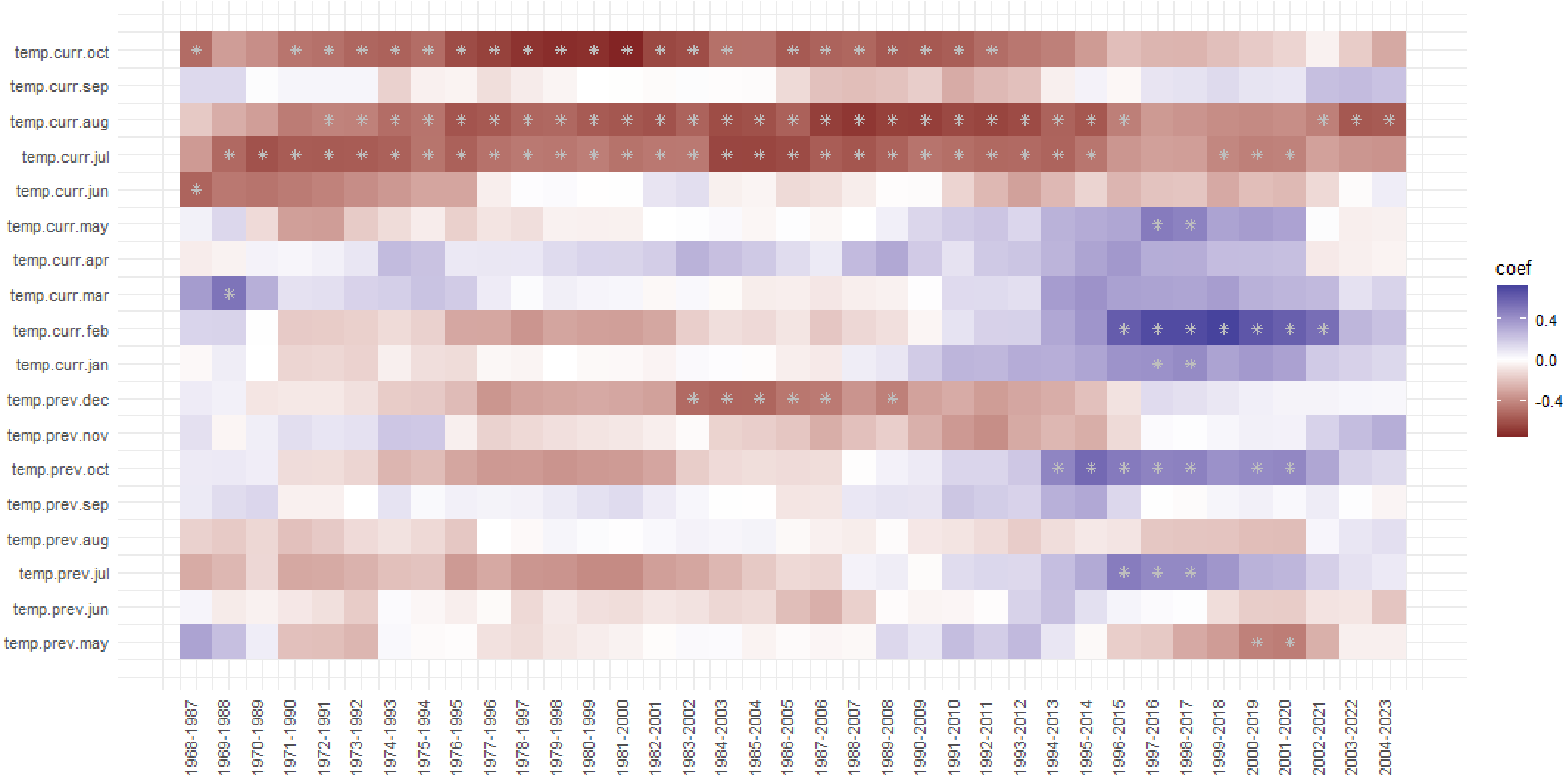
Static correlation analysis of temperature with RWI in provenance Ukiah (P1008)



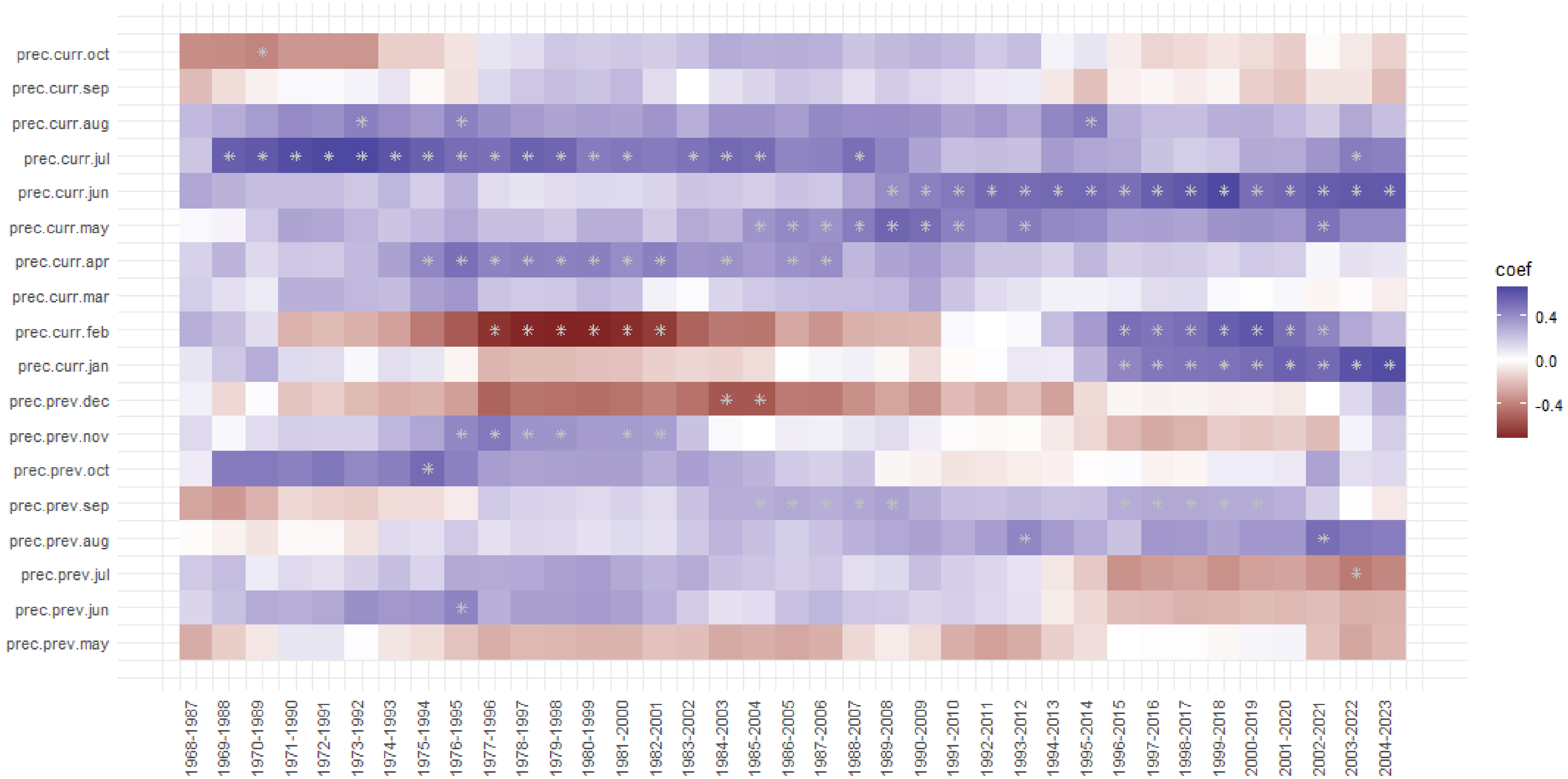
Static correlation analysis of precipitation with RWI in provenance Ukiah (P1008)



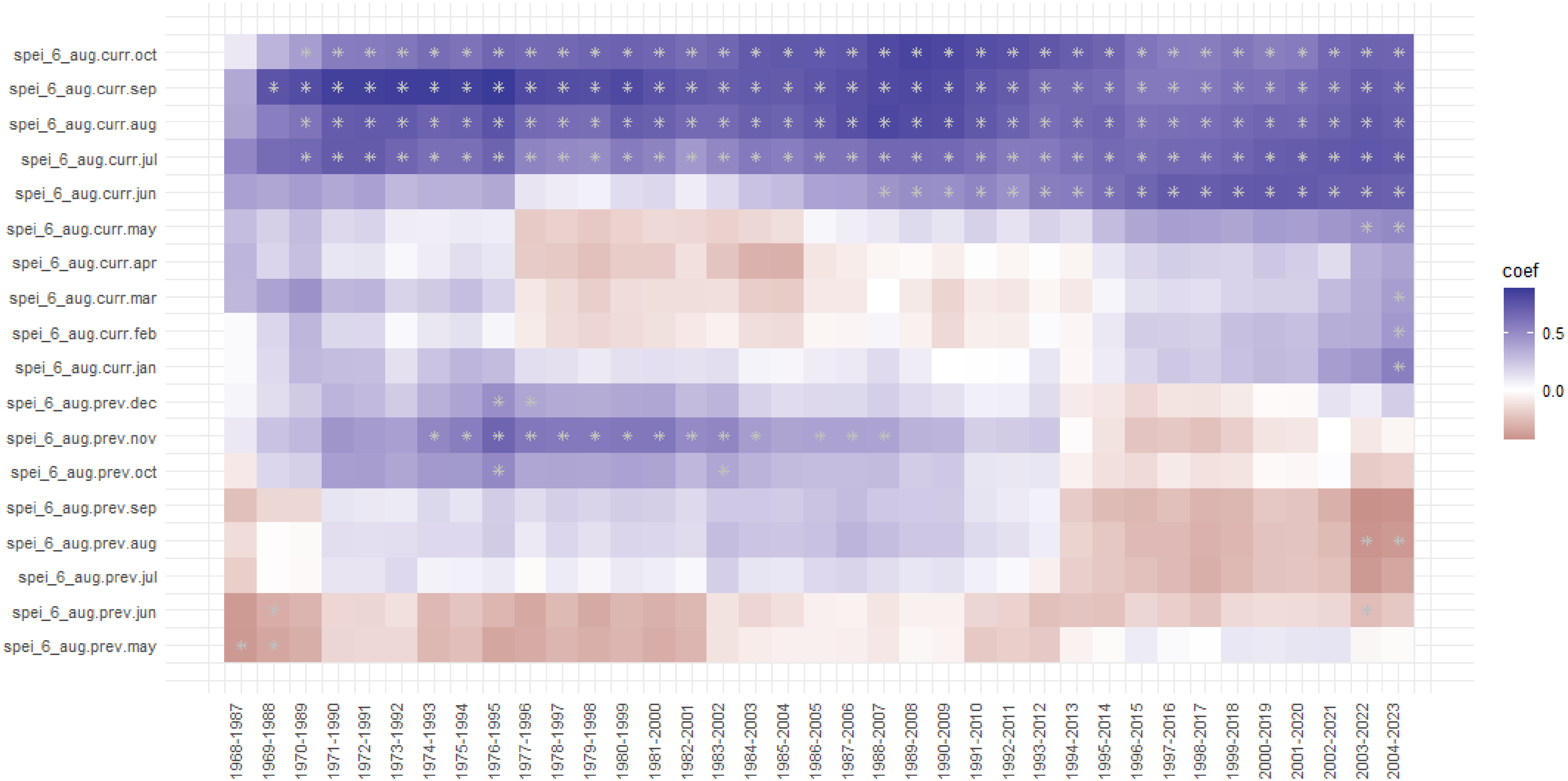
Moving correlation analysis of temperature with RWI in provenance Navarro (P1010-1011)



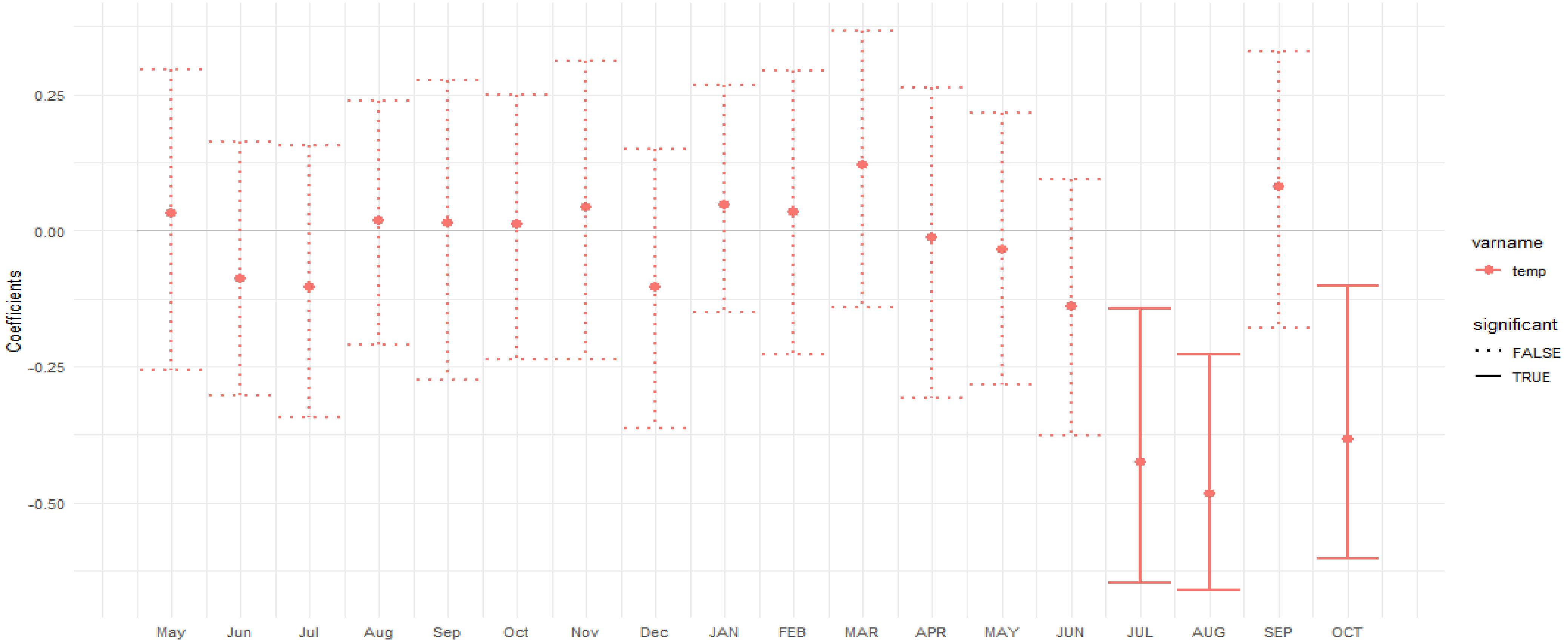
Moving correlation analysis of precipitation with RWI in provenance Navarro (P1010-1011)



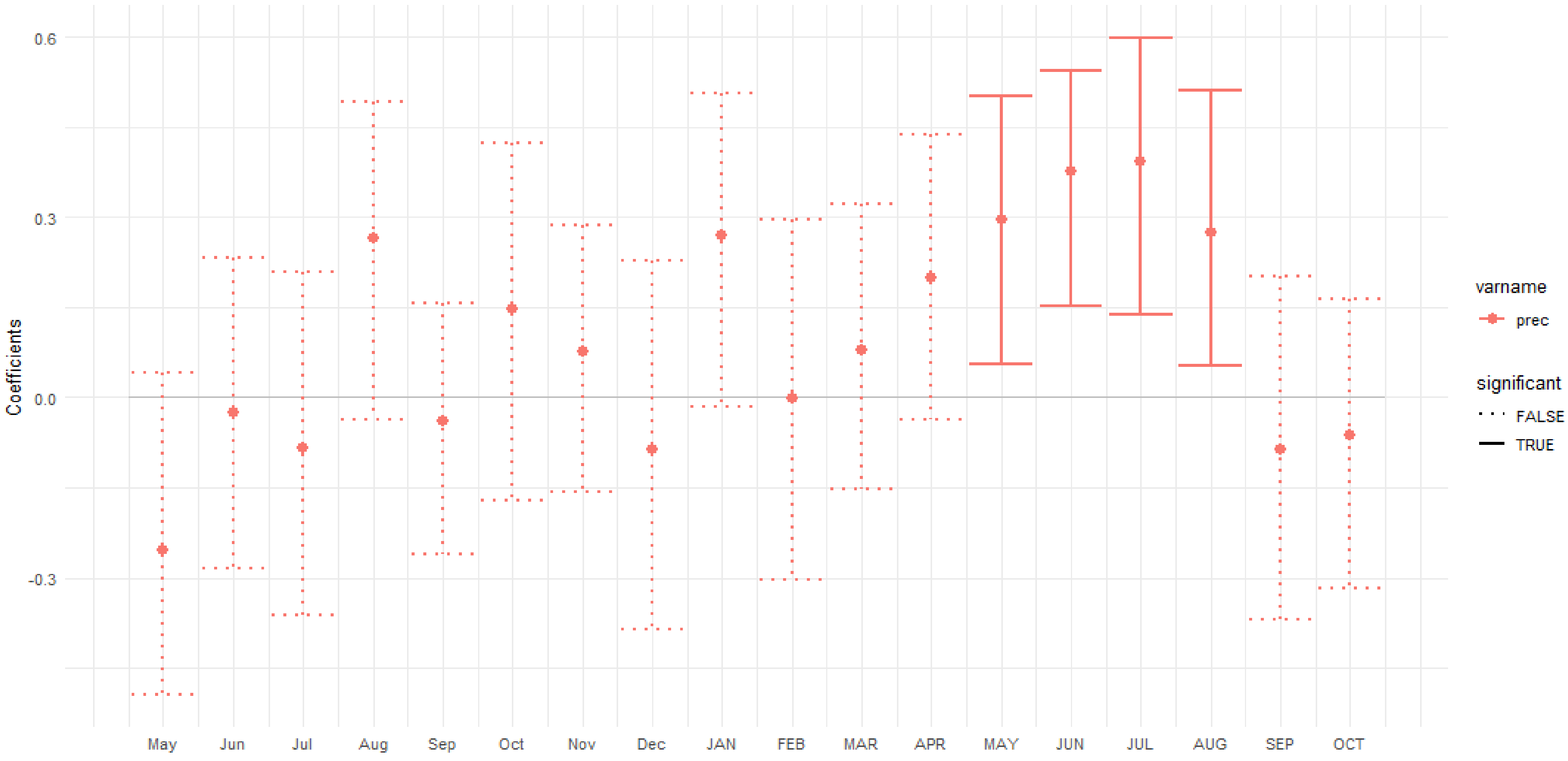
Moving correlation analysis of SPEI with RWI in provenance Navarro (P1010-1011)



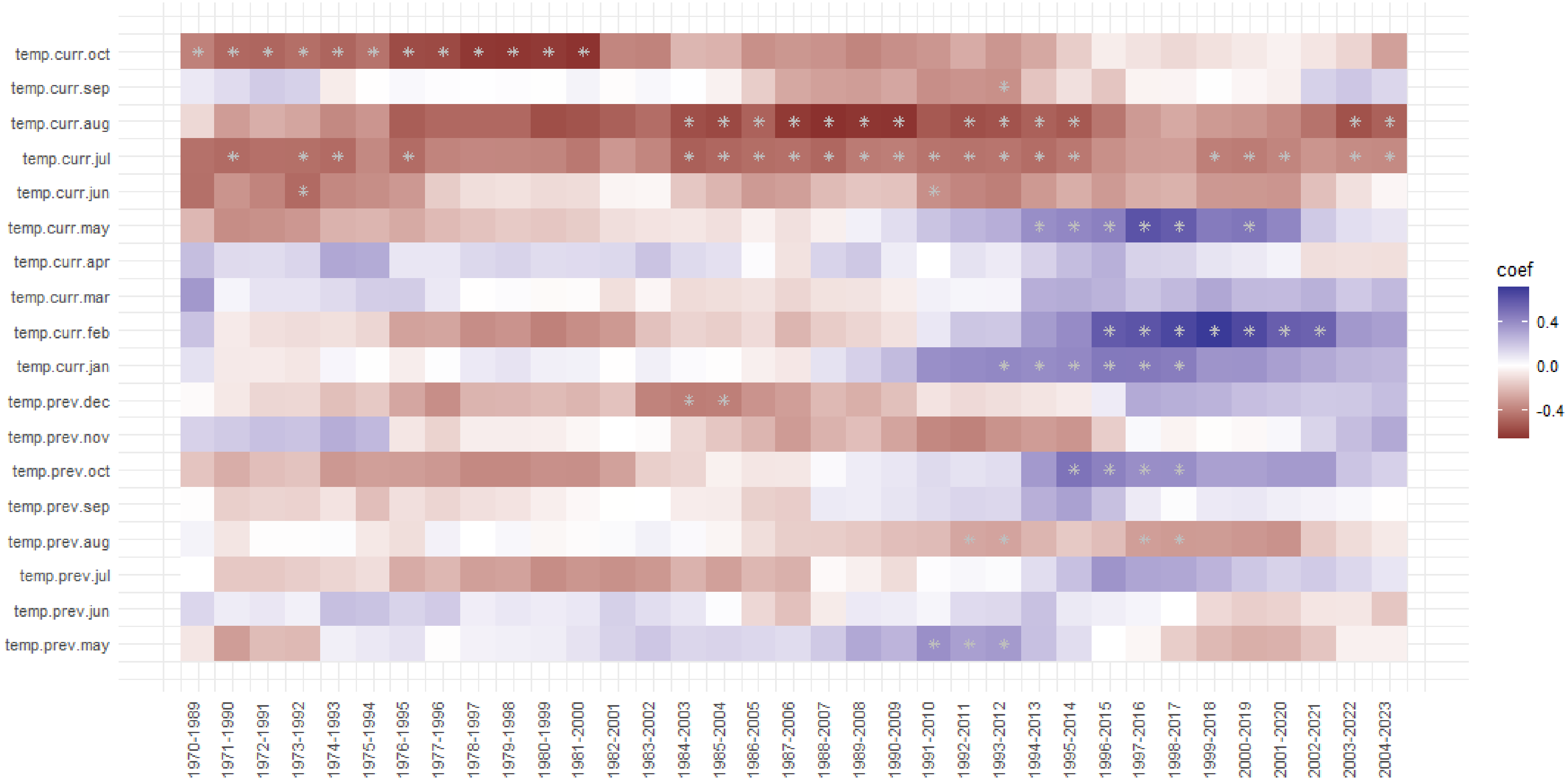
Static correlation analysis of temperature with RWI in provenance Navarro (P1010-1011)



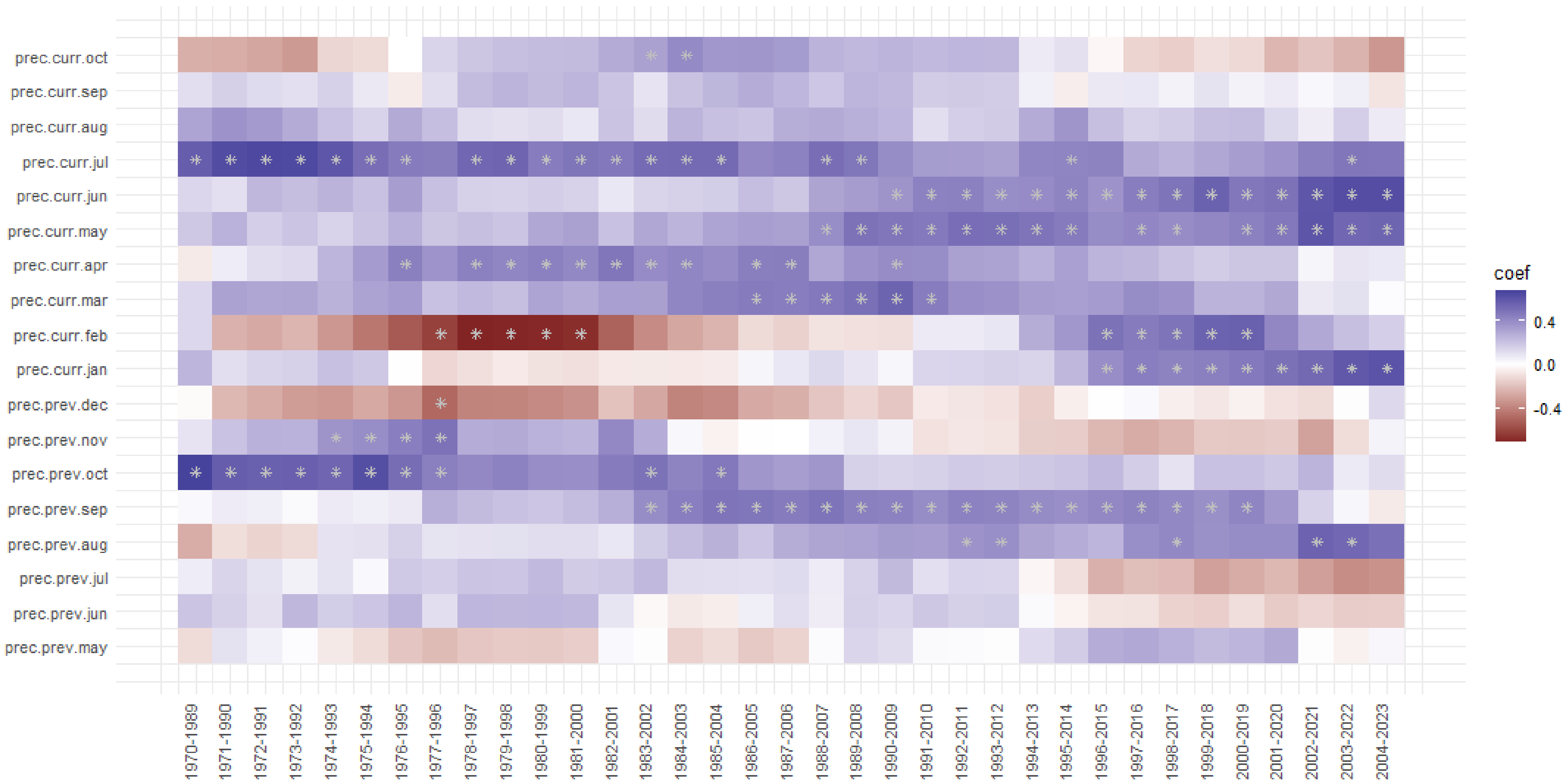
Static correlation analysis of precipitation with RWI in provenance Navarro (P1010-1011)



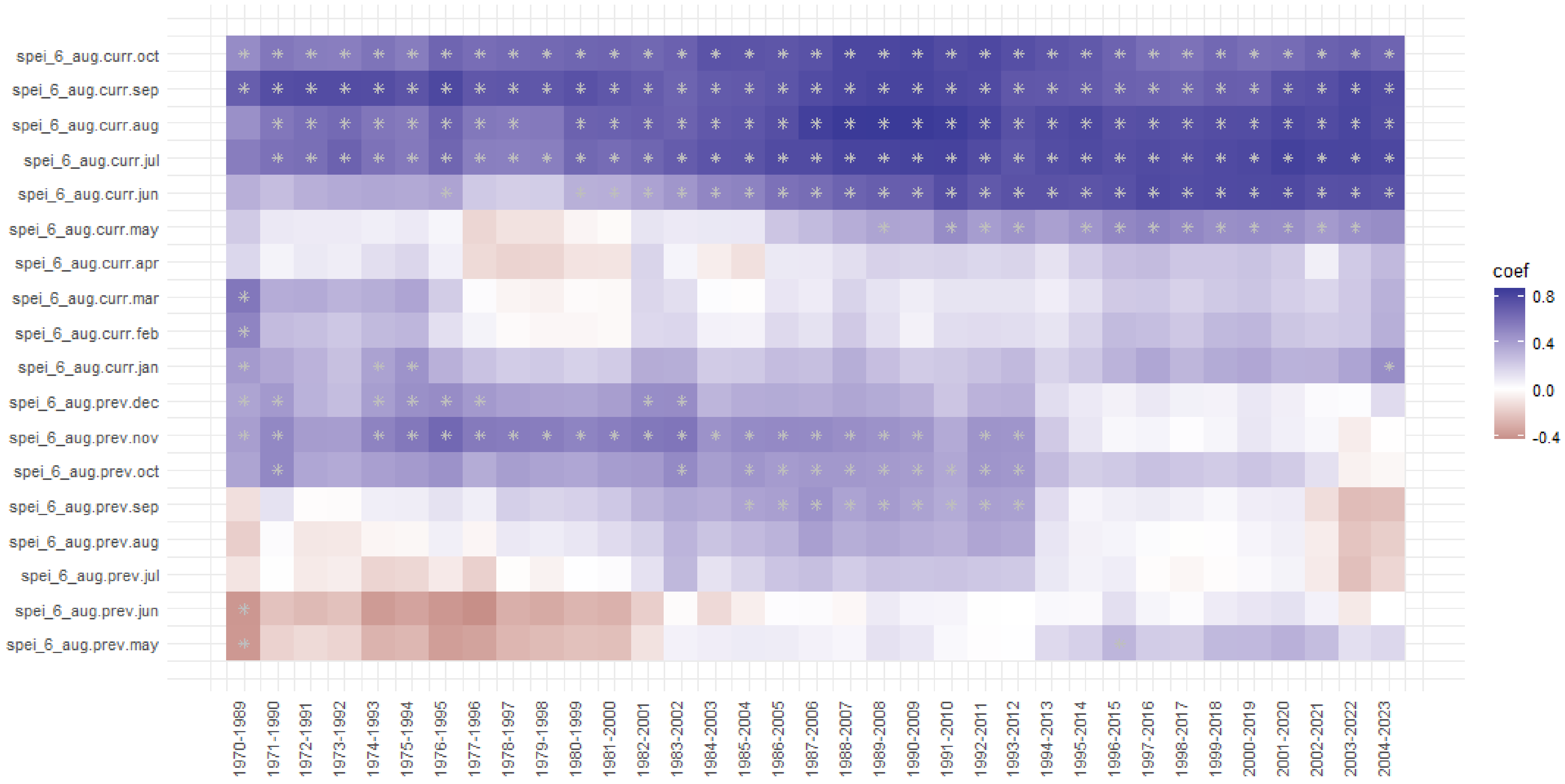
Moving correlation analysis of temperature with RWI in provenance Napa (P1016-1017-1018)



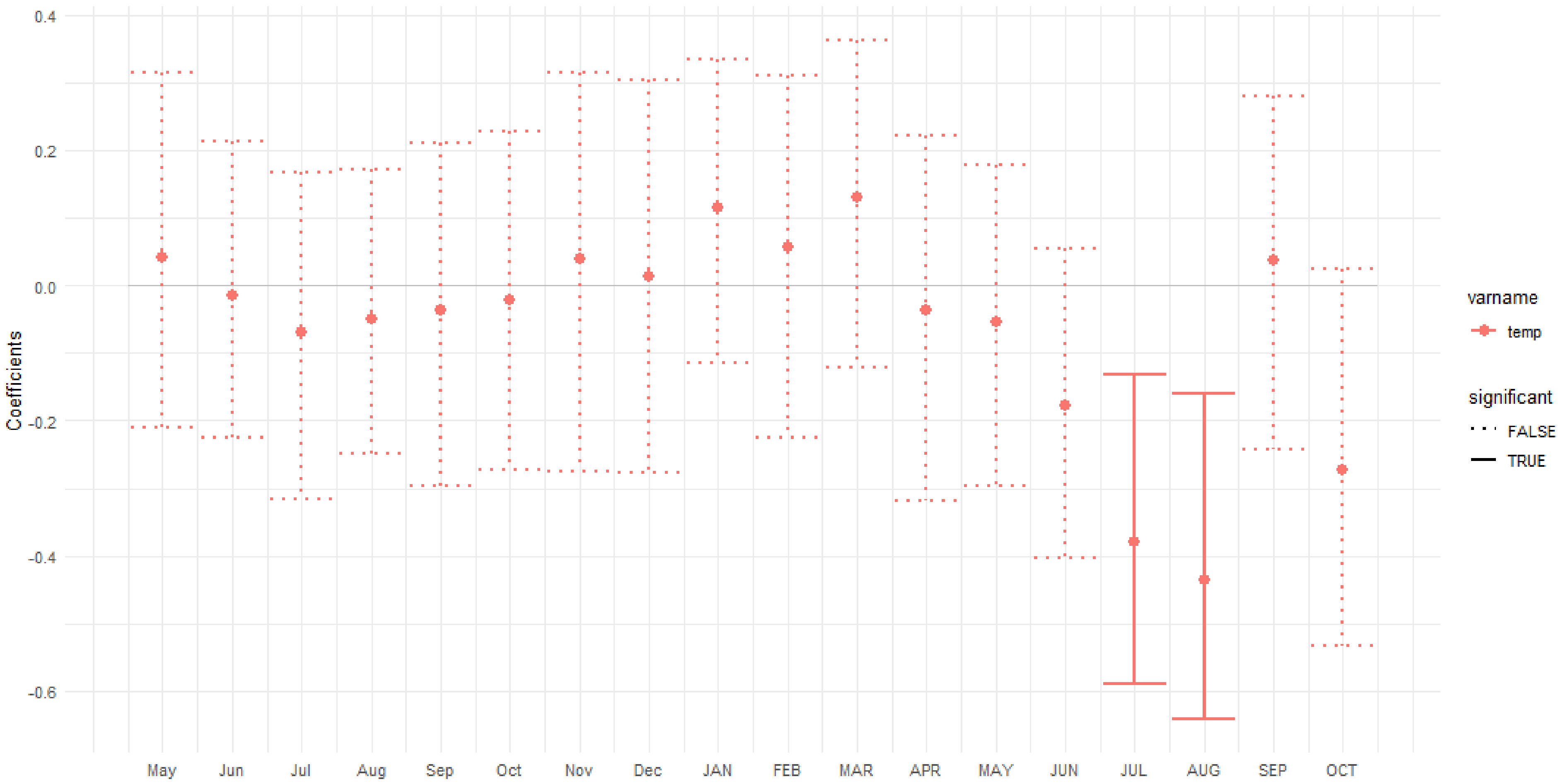
Moving correlation analysis of precipitation with RWI in provenance Napa (P1016-1017-1018)



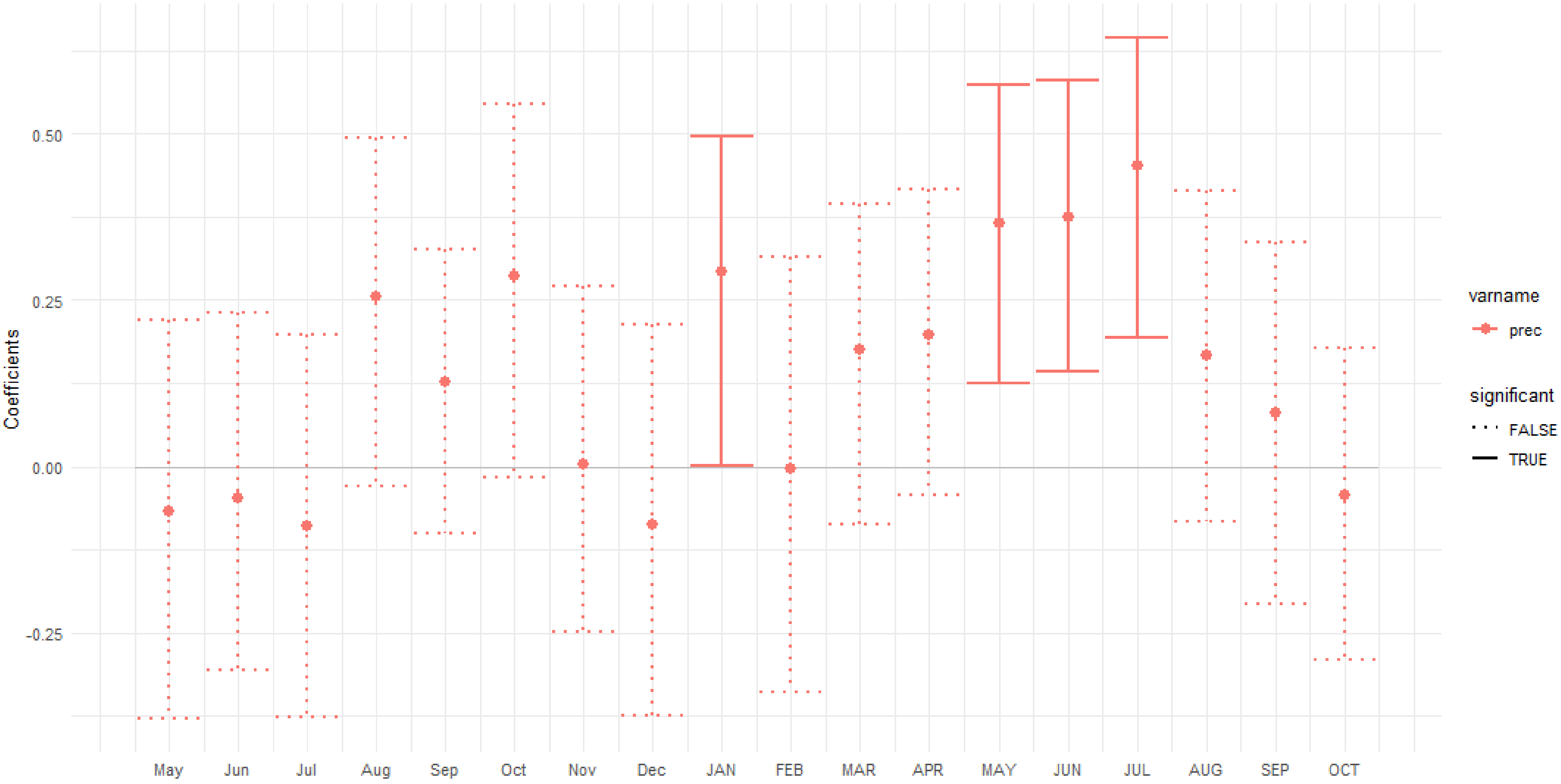
Moving correlation analysis of SPEI with RWI in provenance Napa (P1016-1017-1018)



Static correlation analysis of temperature with RWI in provenance Napa (P1016-1017-1018)



Static correlation analysis of precipitation with RWI in provenance Napa (P1016-1017-1018)



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