Do Southern Hemisphere tree rings record past volcanic events? A case study from New Zealand

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Abstract

Much of our knowledge about the impacts of volcanic eruptions on climate comes from proxy records. However, little is known about their impact on the low to mid-latitudes of the Southern Hemisphere. Using superposed epoch analysis, we investigated whether volcanic signals could be identified in annual tree-ring series from eight New Zealand dendrochronological species. We found that most species are reliable recorders of volcanic cooling and that the magnitude and persistence of the post-event response can be broadly linked to plant life-history traits. Across species, site-based factors, particularly altitude and exposure to prevailing conditions, are more important determinants of the strength of the volcanic response than the species. We then investigated whether chronology selection impacts the magnitude of post-volcanic cooling in tree-ring based temperature reconstructions by developing two new multispecies reconstructions of New Zealand summer (December-February) temperature with one reconstruction from the pool of all available chronologies, and the other from a selected subset shown to be sensitive to volcanic eruptions. Both reconstructions record temperature anomalies remarkably consistent with studies based on instrumental temperature, and with the ensemble mean response of climate models, demonstrating that New Zealand ring widths are reliable indicators of regional volcanic climate response. However, we also found that volcanic response can be complex, with positive, negative, and neutral responses identified - sometimes within the same species group. Species-wide composites thus tend to underestimate the volcanic response. This has important implications for the development of future tree ring and multiproxy temperature reconstructions from the Southern Hemisphere.

1 Introduction

Emissions from large volcanic eruptions are a key source of temperature and hydroclimate variability on interannual to decadal time scales (Robock, 2005; Iles et al., 2013). As few large volcanic eruptions have occurred during the instrumental era, much

of our knowledge about volcanic impacts on climate, particularly regional and global temperature, comes from proxy records spanning centuries to millennia (Tejedor et al., 2021; Wilson et al., 2016; D'Arrigo et al., 2013). These records are predominantly high altitude or high latitude tree-ring proxies from the Northern Hemisphere (e.g. Briffa et al., 1998; D'Arrigo et al., 2009; Pieper et al., 2014). In comparison, there are very few proxy-based characterisations of the temperature response to volcanic events from the Southern Hemisphere (Tejedor et al., 2021; Neukom et al., 2014). The limited number of studies considering Southern Hemisphere tree-ring proxies have generally not found significant impacts following what are considered 'large' volcanic eruptions (Krakauer and Randerson, 2003; Palmer and Ogden, 1992; Allen et al., 2018; Cook et al., 1992). Two eruptions (Santa Maria in 1902 and Agung in 1963) have been identified in tree-ring sites spanning South America, but the impacts of other eruptions on growth have proved less conclusive (Villalba and Boninsegna, 1992).

Whether the hemispheres have contrasting sensitivities to volcanic eruptions is vital to understanding future climate projections (Neukom et al., 2014). The muted volcanic impact in Southern Hemisphere proxy reconstructions could be due to a maritime dampening effect on post-eruption cooling and/or the distribution of landmasses toward the Equator (Raible et al., 2016; Krakauer and Randerson, 2003; Allen et al., 2018). Such explanations suggest the magnitude of Southern Hemisphere cooling is too small to be reliably recorded in tree-ring archives. However, climate models show a clear Southern Hemisphere volcanic signal via reduced mean surface air temperatures (Neukom et al., 2014, 2018). There are several potential explanations for the discrepancy between proxy reconstructions and climate models in the Southern Hemisphere. These include the underestimation of the moderating effects of the ocean on post-eruption cooling in climate models, changes to the hydrological cycle in response to volcanic cooling, uncertainties in volcanic forcing data, and/or proxy noise and spatial distribution (Neukom et al., 2018; Zhu et al., 2020).

The question remains as to whether Southern Hemisphere proxies – specifically tree rings - do record volcanic events. To our knowledge, no studies have explored the factors which influence whether (or not) volcanic signals can be identified using tree-ring data from the Southern Hemisphere. Tree growth depends on a range of environmental and biological factors, so careful site and tree selection is necessary to ensure that a specific influence of interest can be studied (Norton and Ogden, 1987). Northern Hemisphere tree-ring studies are predominantly from high-latitudes or mid-latitude alpine treeline sites where tree growth is temperature limited (Scuderi, 1990). Around 80% of chronologies from such sites show significant growth reductions following large eruptions due to unusually low growing-season temperatures (Krakauer and Randerson, 2003). For high latitude sites, decreased light availability after eruptions also contributes to the strong growth reduction (Tingley et al., 2014). Tree-ring studies from Northern Hemisphere mid-latitude lowland sites have shown that volcanic response is less clear, as temperate zone trees are less temperature-limited and have more complex relationships to multiple climate variables (Pieper et al., 2014; Wilson et al., 2016).

Exploring possible responses to volcanic eruptions, Pieper et al. (2014) proposed three modes for tree growth in temperate regions: 1) Growth reduction due to decreased growing season temperature, resulting in narrow rings; 2) Neutral/ no response if the climate sensitivity to volcanic eruptions is insufficient to influence tree growth; or 3) Enhanced growth due to an increase in the diffuse light fraction and reduced water stress, resulting in wide rings. Temperate-zone trees from the Southern

Hemisphere are also likely to display similar mixed volcanic signals, depending on their relative sensitivity mode and the magnitude of the regional cooling effect. Understanding these factors will help elucidate the proxy archive contribution to the Southern Hemisphere model-data discrepancy. This knowledge will benefit future studies of hemispheric temperatures and help identify which species and/or regions should be prioritised for future proxy development.

75 Our goal in this study is to assess whether Southern Hemisphere tree rings record past volcanic events using a multispecies network of high-quality, replicated tree-ring chronologies from New Zealand. This country is a long, narrow, archipelagic landscape stretching from 34°S to 47°S. Climatically, the northern part protrudes into the warm sub-tropical ridge, whereas the southern end is embedded in the cool southwesterlies (Salinger, 1980). The North and South Island axial ranges, which rise to 3,764 m, are a significant barrier to east-west airflow, leading to strong regionalisation of precipitation anomalies

80 (Salinger, 1980). Land clearing has resulted in the loss of forests from most lowland areas and nearly all of the eastern drylands. The most common remaining forest types are wet conifer-broadleaved forests and montane to alpine southern beech (*Nothofagaceae*) dominated forests (McGlone et al., 2017).

Tree-ring chronologies have been developed from locations widely distributed throughout New Zealand. Since the initial dendrochronological studies undertaken by LaMarche et al. (1979), records have been generated from nine endemic species,

85 of which seven are conifers, and two are *Nothofagaceae* (Table 1). Five main species have been used to develop multi-centennial tree-ring chronologies: kauri (*Agathis australis*), pink pine (*Halocarpus biformis*), silver pine (*Manoao colensoi*), cedar (*Libocedrus bidwillii*), and silver beech (*Lophozonia menziesii*). Most chronologies are primarily sensitive to austral summer temperatures, with temperature reconstructions developed from beech (Norton et al., 1989), silver pine (Cook et al., 2002), cedar (Palmer and Xiong, 2004), pink pine (Duncan et al., 2010), and multispecies networks (Salinger et al., 1994).

90 Thus, New Zealand, with its wide latitudinal and altitudinal range, regionalised climate zones, and wide distribution of tree-ring chronologies from multiple species – including some instances of multiple species from the same site - is ideal for studying tree-ring sensitivities to past volcanic events. Using the New Zealand dendrochronological dataset, we aim to answer the following specific questions:

1. Can we identify volcanic signals in high-quality tree-ring series from the Southern Hemisphere?

95 2. Are there differences in the expression of volcanic signals amongst the species?

3. Does chronology selection impact the magnitude of post-volcanic cooling in tree-ring based temperature reconstructions?

2 Data and methods

2.1 Tree-ring chronologies

100 The New Zealand tree-ring chronologies analysed in this study were collated to develop the Eastern Australia and New Zealand Drought Atlas (Palmer et al., 2015; Fig. 1). Palmer et al. (2015) identified chronologies from the International Tree Ring Data Bank and personal collections, screened the tree-ring measurements for dating problems using the software program

COFECHA (Holmes., 1983; Grissino-Mayer, 2001) and developed site 'master' chronologies from the raw ring widths using the 'signal free' method of standardisation (Melvin and Briffa, 2008). The metadata for all New Zealand chronologies are provided in Table S1. As only a single chronology has been developed from mountain toatoa (*Phyllocladus alpinus*) it was excluded from the study, leaving a pool of 96 chronologies from 8 dendrochronological species for volcanic response analysis.
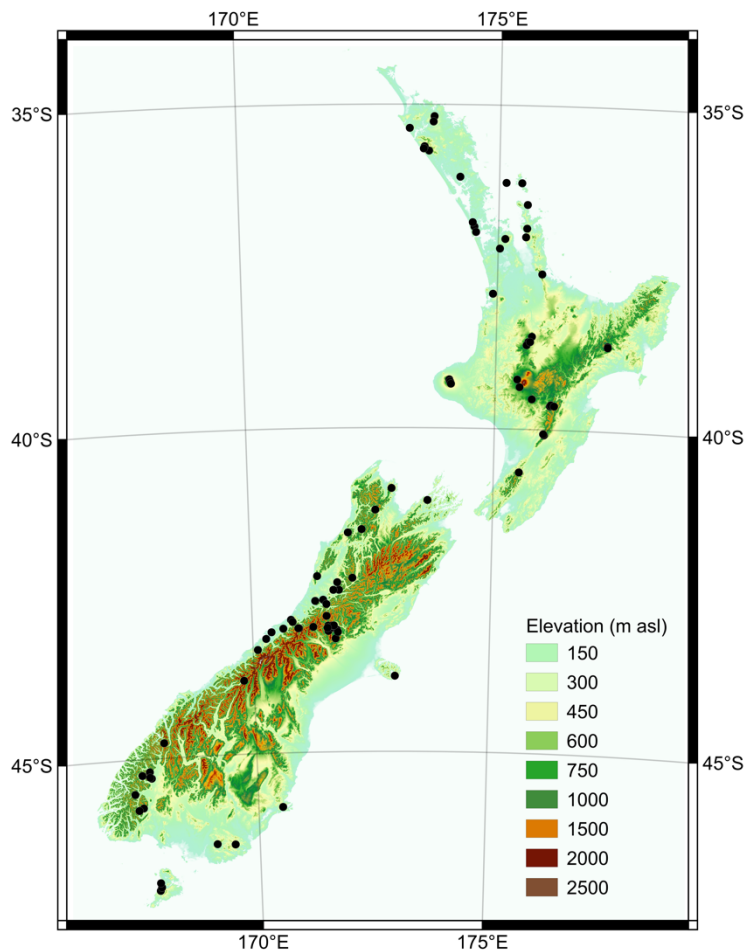
Figure 1 – Distribution of tree-ring chronologies in New Zealand. Elevation data sourced from the LINZ Data Service and licenced for reuse under CC BY 4.0.

Table 1 summarises the distribution, average climate responses, and main wood properties (average annual ring growth and temporal correlation or persistence) of the species, as described by the studies documenting the development of the chronologies. In addition, the response of each species to average New Zealand monthly temperatures, calculated for this study, is also summarised. All species show significant (p < 0.05) relationships with average New Zealand temperatures (Salinger, 1981; Mullan, 2012) during individual months of the current growing season, except toatoa (Table 1, Fig. S1-S6). Tree growth is only weakly correlated with average monthly temperatures, with |r| < 0.3 for most chronologies. Pink pine shows stronger correlations with summer temperatures, with r values of 0.4-0.6. Pine pink is also significantly correlated to

temperatures over the entire growing season, whereas the other species are seasonally restricted with significant correlations to peak summer temperatures only. Most species are positively correlated to current season temperatures, with wider ring widths associated with warm years; however, kauri and beech show an inverse relationship to temperature, with warm temperatures restricting growth. Cedar, silver pine, mountain beech and both *Phyllocladus* species show stronger sensitivities to prior than current season temperatures (Fig. S1-S6).

2.2 Selection of volcanic events

Event selection is a significant source of uncertainty in tree-ring studies of volcanic cooling. The choice of volcanic events can greatly influence the magnitude of average regional cooling identified (Esper et al., 2013; Wilson et al., 2016). In addition, for many events which occurred before instrumental records, the timing, location, and size of eruptions are uncertain (Timmreck et al., 2021; Garrison et al., 2018). For this analysis, we are interested in those events which would likely have reduced growing season temperatures over New Zealand and thus be identifiable as ring-width anomalies. Therefore, we selected events using a regional volcanic dimming threshold rather than an eruption magnitude. Prior to the instrumental era, we picked events from the Greenland and Antarctic ice core sulphate aerosol analysis of Toohey & Sigl (2017) based on peak stratospheric atmospheric aerosol depth (SAOD). We averaged SAOD, modelled using the Easy Volcanic Aerosol module (Toohey et al., 2016) over the latitudinal range of New Zealand (30 to 50° S). The SAOD magnitude corresponding to a substantial temperature response is unknown before analysis. However, selecting a magnitude post-analysis based on the observed response risks biasing the results (Haurwitz and Brier, 1981). Therefore, two different SAOD thresholds were used: SAOD > 0.08, which resulted in 10 eruptions for analysis between 1400 and 1900 CE; and SAOD > 0.04, resulting in 18 eruptions for the same period (Fig. 2). Between 1900 and 1990, we selected the three largest tropical eruptions, which have been shown to have significant impacts on instrumental temperatures in New Zealand (Salinger, 1998). At each methodological step, the analysis was carried out using both the 13 (10 pre-1900 events plus 3 post-1900) and 21 (18 pre-1900 events plus 3 post-1900) event lists separately. Full details of all selected eruptions are provided in Table S2.
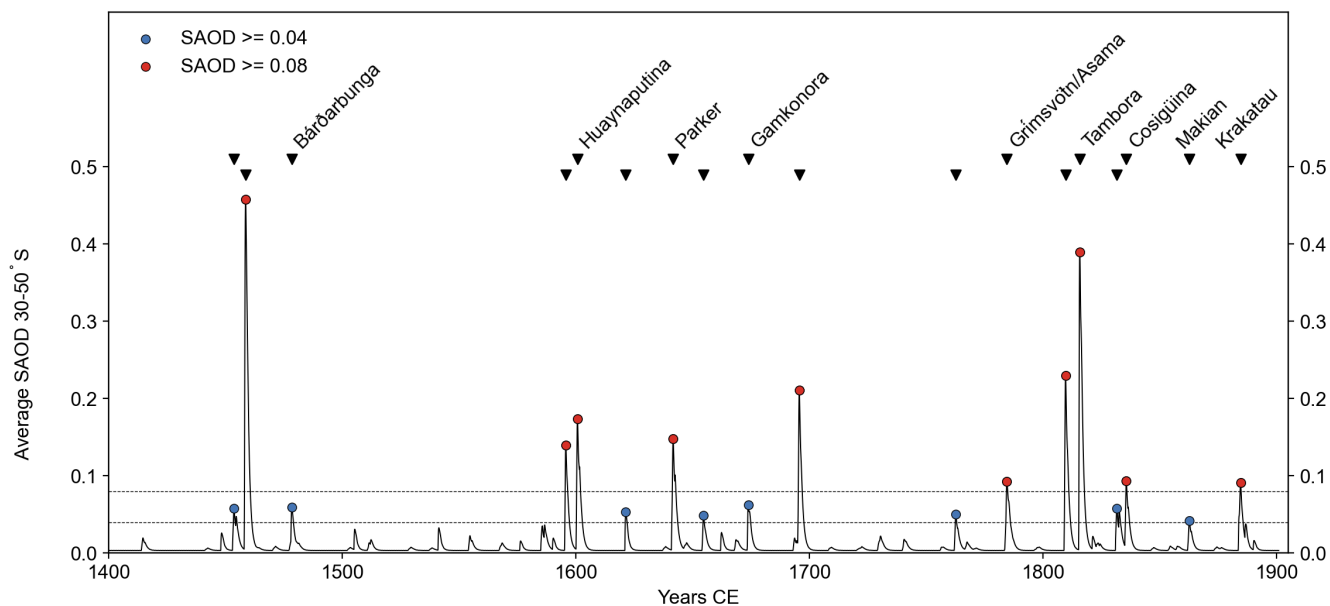
Figure 2 – Selection of volcanic events based on thresholds of peak modelled stratospheric atmospheric optical depth (Toohey and Sigl, 2017), **averaged over 30-50 ºS, greater than 0.04 (blue) and 0.08 (red). Known eruptions are labelled.**

2.3 Superposed epoch analysis

We tested whether a volcanic signal can be identified in New Zealand tree-ring chronologies using superposed epoch analysis (SEA; (Haurwitz and Brier, 1981)), a statistical technique widely used to determine the impacts of volcanic eruptions on climate (Rao et al., 2019; Adams et al., 2003; Scuderi, 1990; Salinger, 1998; Tejedor et al., 2021). The composite response of individual chronologies to the 13 largest eruptions and the 21 full eruption list between 1400 and 1990 CE was studied 0 - 5 years post-event, with anomalies calculated by subtracting the average of the nearest 5-year background period undisturbed by volcanic forcing (Table S2; (Büntgen et al., 2020)). Species-level responses were then tested using a composite chronology produced by simple averaging of annual values across sites (Cook and Kairiukstis, 1990). Volcanic responses were categorised as positive or negative if the anomalies exceeded the 5th or 95th percentile response of 10,000 random samples of years undisturbed by volcanic forcing, or neutral if they fell between these bounds.

2.4 Temperature reconstructions

To investigate the influence of chronology selection on the identification of volcanic signals in temperature reconstructions, we report two new reconstructions of New Zealand summer temperatures (December-February). We used the New Zealand average 'seven-station' monthly instrumental temperature series (Salinger, 1981; Mullan, 2012), obtained from the New Zealand National Institute of Water and Atmospheric Research (NIWA), to examine the temperature response of the chronologies. Correlations were calculated between autoregressively modelled chronologies and monthly climate data, with

160   each month treated as a separate time series. A 20-month window was selected for correlation analysis, extending from October of the previous growing season to May at the end of the current austral growing season. Two growing seasons were included as significant prior season climate sensitivities have been reported for some species. Based on the response analysis, December-February (DJF) was selected as the seasonal target, as this window captures the strongest correlations across all species (Table 1).

165   To ensure sufficient overlap between the chronologies and the temperature dataset for calibration and verification, only chronologies extending to or beyond 1990 were retained for the reconstructions. As many sites have not been updated since they were originally sampled in the 1970/80s, only 58 of the 96 chronologies were retained. The first reconstruction (NZall) included the full suite of available chronologies extending to 1990, while the second (NZsel) was limited to those chronologies which showed a significant volcanic signal using SEA. In each case, only those chronologies significantly ($p < 0.1$) correlated

170   to average DJF temperatures over the period 1911-1990 were used. The tree-ring series were also tested as potential predictors with a lag of one year with respect to the temperature data, as prior climate often has a lingering influence on current year tree growth (Fritts, 1976; Table 1). Average DJF temperatures were reconstructed using nested principal components linear regression (Cook et al., 2007, 2010, 1999). A 50:50 split calibration-validation scheme was used, in which the model was initially calibrated on the first half of the data (1911-1950) and validated on the second half (1951-1990), then the model was

175   re-estimated with the calibration and validation periods reversed. Once the split models were verified based on the verification period reduction of error (VRE) and verification period coefficient of efficiency (VCE; (Cook and Kairiukstis, 1990)) metrics, the entire data period was used to produce the final reconstructions (Briffa et al., 1990).

    The volcanic response in tree-ring reconstructions of temperature was also tested using SEA and the two sets of volcanic eruption years. Further, variation in the temperature response to different volcanic events was estimated by calculating the

180   90th percentile bootstrap confidence interval from 1,000 replicates drawn without replacement from the event list (Rao et al., 2019). In each iteration, approximately two-thirds (9/13 or 15/21) of the volcanic events were selected. The confidence interval provides some indication of how eruptions of different sizes, locations, and seasonality may impact the SEA results. To further assess how event selection may have affected the SEA results, the analysis was repeated using volcanic events selected from the ice core analysis of Crowley & Unterman (2013), using a Southern Hemisphere-average threshold of SAOD > 0.08 and

185   SAOD > 0.04 rather than a regional threshold (Table S3).

    We compared the volcanic response seen in our multispecies reconstructions to the ensemble mean DJF response of seven climate models from the Coupled Model Intercomparison Project 5 (CMIP5) suite with Last Millennium (past1000, 850-1850 CE) simulations. The CMIP5 models were forced with either the Gao et al. (2008) or Crowley and Unterman (2013) volcanic forcing series (see Table S4). Data from the historical simulations were appended to extend the dataset from 1850 to 2005.

Table 1 – Distribution, reported climate sensitivities, and key references for New Zealand dendrochronological species

Code	Species	Common name	No. chronologies	Ring width (mm/y)	Persistence (GINI²)	Distribution	Reported climate sensitivity	Temperature sensitivity[3]	Chronology development
AGAU	*Agathis australis*	Kauri	17 (9*)[1]	1.66 ± 0.59	0.106	North Island, north of 38°S; predominantly lowland forests, can be > 500 m	ENSO; inverse relationship to current year temperature and precipitation.	Inverse relationship to current summer temperatures.	(Boswijk et al., 2006; Buckley et al., 2000; Fowler et al., 2008; LaMarche et al., 1979; Ogden & Ahmed, 1989; Palmer et al., 2006)
HABI	*Halocarpus biformis*	Pink pine	20 (19*)	0.44 ± 0.1	0.074	Low altitude to sub-alpine; central North Island to Stewart Island	Frost tolerant; sensitive to year-round temperatures	Current growing season (P); prior summer (S).	(R. D. D'Arrigo et al., 1996; Fenwick, 2003; Xiong et al., 1998)
LACO	*Manoao colensoi* (formerly *Lagerostrobos colensoi*)	Silver pine	6 (4)	0.56 ± 0.20	0.065	Low-elevation forests of the South Island west coast and some North Island locations.	Summer temperatures	Inverse relationship to prior autumn (P); Current summer/ autumn (S).	(Cook et al., 2002; R. D. D'Arrigo et al., 1998)
LIBI	*Libocedrus bidwillii*	New Zealand cedar	26 (21)	0.7 ± 0.17	0.091	Widely distributed over North and South Islands south of 38°S; 200 to 1200 m above sea level	Summer temperatures, precipitation	Inverse relationship to prior summer (P); Current summer (S).	(LaMarche et al., 1979; Xiong & Palmer, 2000)
NOME	*Lophozonia menziesii* (formerly *Nothofagus menziesii*)	Silver beech	7 (1)	1.14 ± 0.24	0.136	Montane and subalpine forests, common in the South Island	Summer temperatures	Inverse relationship to prior summer/ autumn (P); Current summer (S).	(Norton, 1983b, 1984)
NOSO	*Fuscospora cliffortioides* (formerly *Nothofagus solandri* var. *cliffortioides*)	Mountain beech	11 (4)	0.92 ± 0.23	0.136	Closed forests of the central North Island and the eastern South Island, valley floor to ~1300 m	Summer temperatures	Inverse relationship to prior summer/ autumn (P); Mixed current summer signal (S).	(Norton, 1983a, 1984)
PHAL	*Phyllocladus alpinus*	Mountain toatoa	1	0.59 ± 0.22	0.065	Throughout New Zealand, lowland to subalpine forests	N/A	N/A	(LaMarche et al., 1979)
PHGL	*Phyllocladus toatoa* (formerly *P. glaucus*)	Toatoa	4	0.63	0.129	North Island, montane forest between 850 and 1000 m	Summer temperatures, precipitation, pressure anomalies	Inverse relationship to prior summer/ autumn.	(Dunwiddie, 1979; LaMarche et al., 1979; Palmer, 1989; Salinger et al., 1994)
PHTR	*Phyllocladus trichomanoides*	Tanekaha	5	1.04	0.118	Lowland forest up to 800 m above sea level, north of 42°S	Summer temperatures, precipitation, pressure anomalies	Inverse relationship to prior summer/ autumn.	(Dunwiddie, 1979; LaMarche et al., 1979; Palmer, 1989; Palmer & Ogden, 1992; Salinger et al., 1994)

[1] Number in brackets indicate the number of chronologies extending to 1990 available for the temperature reconstructions. *Includes master chronology.

[2] GINI coefficient – an all-lag measure of diversity in tree-ring records (Biondi & Qeadan, 2008)

[3] Summary of sensitivity to New Zealand average temperatures, calculated for this study (see also Figures S1 to S6). Where significant relationships to both prior and current season temperatures exist, P indicates the primary (dominant) sensitivity and S indicates the secondary sensitivity.

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3. Results

3.1 Overall species volcanic responses

The results of the superposed epoch analysis for the 13 largest volcanic eruptions between 1400 and 1990 CE are shown in Figure 3. Two composite responses are shown for each species; the response averaged across all sites ('All chronology composite'), and the response calculated only from the site chronologies which individually showed a significant (either positive or negative) response to volcanic eruptions ('Sensitive chronology composite'). Analysis was repeated for the full set of 21 eruptions with SAOD > 0.04 with similar, but weaker, results for most species, suggesting that not all events had a measurable climatic impact over New Zealand (Fig. S7).

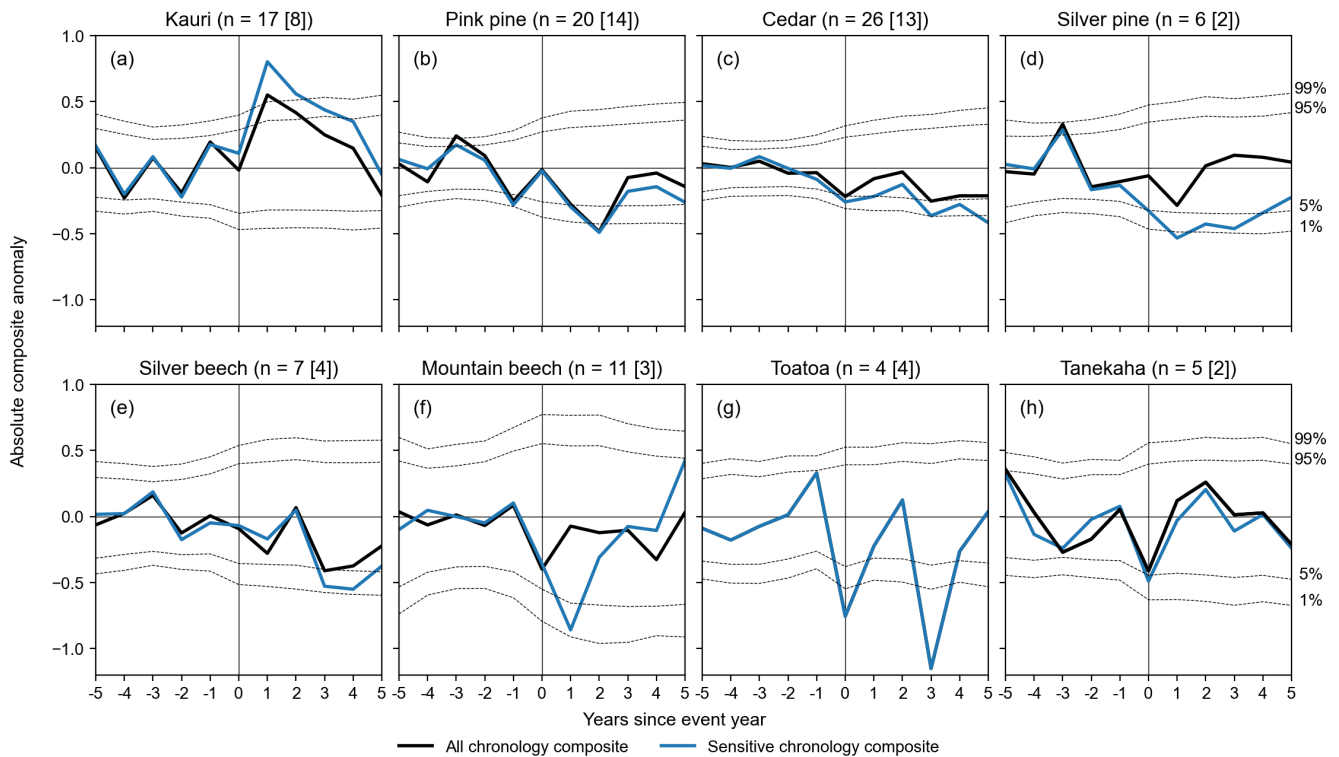



Figure 3 – Mean chronology departures five years before and five years after the 13 largest eruption years (year 0), separated by tree species. The chronologies contributing to the species-wide composite are shown in black, with the number of chronologies indicated in the round brackets. The sensitive chronology composite in shown in blue and the number of contributing chronologies is shown in the square brackets. Significance bands (dotted grey lines) are the 1st, 5th, 95th, and 99th percentile of 10,000 random samples of non-event years from the species-wide composite.

The species-wide response to volcanic events varied widely between New Zealand dendrochronological species. Three out of eight species, silver pine, mountain beech, and tanekaha, recorded a composite neutral response. Tanekaha is only weakly correlated to New Zealand average temperatures (Fig. S6b), which may explain its subdued response. However, compared to

other species, mountain beech and silver pine both show relatively strong temperature sensitivities (Figs. S1a, S4). As many mountain beech chronologies extend only to the mid-1700s, the species composites were tested against a smaller subset of volcanic events, which may contribute to this result.

Of the remaining five species, one recorded a positive response, and four recorded a negative response. Kauri (Fig. 3a) was the only species to show a composite positive response to volcanic events, maximal in year t+1. Kauri showed a consistent response across sites with all except two chronologies showing a positive anomaly following an event, although only 8/17 positive responses were significant at $p < 0.05$. The sensitive chronology composite recorded a very strong t+1 response, indicating that at these eight sites, kauri receives a significant growth benefit from the climatic changes following a volcanic eruption. This response is coherent with the predominant kauri temperature sensitivity, which is an inverse response to current summer temperatures (Fig. S3). However, as most kauri chronologies are only weakly correlated to monthly temperatures, the strong volcanic response suggests climatic changes other than temperature also contribute to the post-event growth benefit.

Pink pine, cedar, silver beech, and toatoa show lagged negative responses to volcanic events, with peak negative anomalies recorded in years t+2 or t+3 (Fig.3 b, c, e, g). The pink pine response is consistent across sites. All except one pink pine chronology recorded a negative response in t+2, which was significant for most of the chronologies (14/21; $p < 0.05$). This response is coherent with the pink pine's broad sensitivity to temperatures over the current growing season (Fig. S2), i.e., cooler spring-summer-autumn temperatures supress growth across most pink pine sites. Similarly, the negative silver beech response is coherent with its current season temperature sensitivity (Fig. S1b) although neither the temperature correlation nor the volcanic response is particularly strong. All four toatoa chronologies recorded a significant negative response in t+3. However, as toatoa shows only weak lagged correlation with monthly temperatures (Fig. S6a), the link between temperature sensitivity and volcanic response is not easily elucidated.

In contrast, cedar does not show a consistent species-wide response; both significant negative and positive responses were recorded in 13/26 chronologies, with the rest showing a neutral response. This is despite a largely consistent within-species temperature sensitivity, which is an inverse response to prior season temperatures (Fig. S5).

3.2 Within-species variability in volcanic response

The overall muted species response of cedar masks very different individual chronology responses. Cedar ring-width series respond differently to volcanic events depending on their location, with both very negative and very positive responses recorded. The other species do not show similar variation. The cedar chronologies have the widest geographical distribution of any species, and thus geographical factors may influence the variability in response. We used k-means clustering via principal components analysis (Ding and He, 2004) to investigate whether within-species variation could be explained by obvious factors like regional climate or elevation. Principal components analysis (PCA) was applied to the longest common time interval of the chronologies, 1732-1976 CE, and the first four principal components were retained.

Five chronology groups were identified via clustering (Fig. 4a), broadly corresponding to differences in region and altitude. North Island chronologies were distributed in two groups. All chronologies are from montane to subalpine areas above 800 m,

with groups differentiated between coastal (G1) and inland (G2) locations. A single chronology from the north of the South Island was included in G2. West coast South Island chronologies were also distributed in two groups, differentiating between lowland (G3) and montane (G4) forest. The final grouping (G5) includes three chronologies from the dry eastern lowlands. Strong - but opposing - volcanic responses are identified via clustering. Significant lagged post-eruption growth reduction is identified in groups G1 and G2 from montane to subalpine sites from the North Island, including Takapari (Fig. S8c), and the southern-most grouping, G5. Group three (G3), which includes lowland chronologies from the northwest coast of the South Island, including Ahaura and Flagstaff Creek (Fig. S8d, e), receives a growth benefit in the two years following an eruption similar to that observed in North Island kauri. In cedar, we observed all three of the proposed temperate zone tree responses to volcanic events - positive, negative, and neutral growth - all within a single species, highlighting the importance of site-based factors in determining tree response in temperate zones.

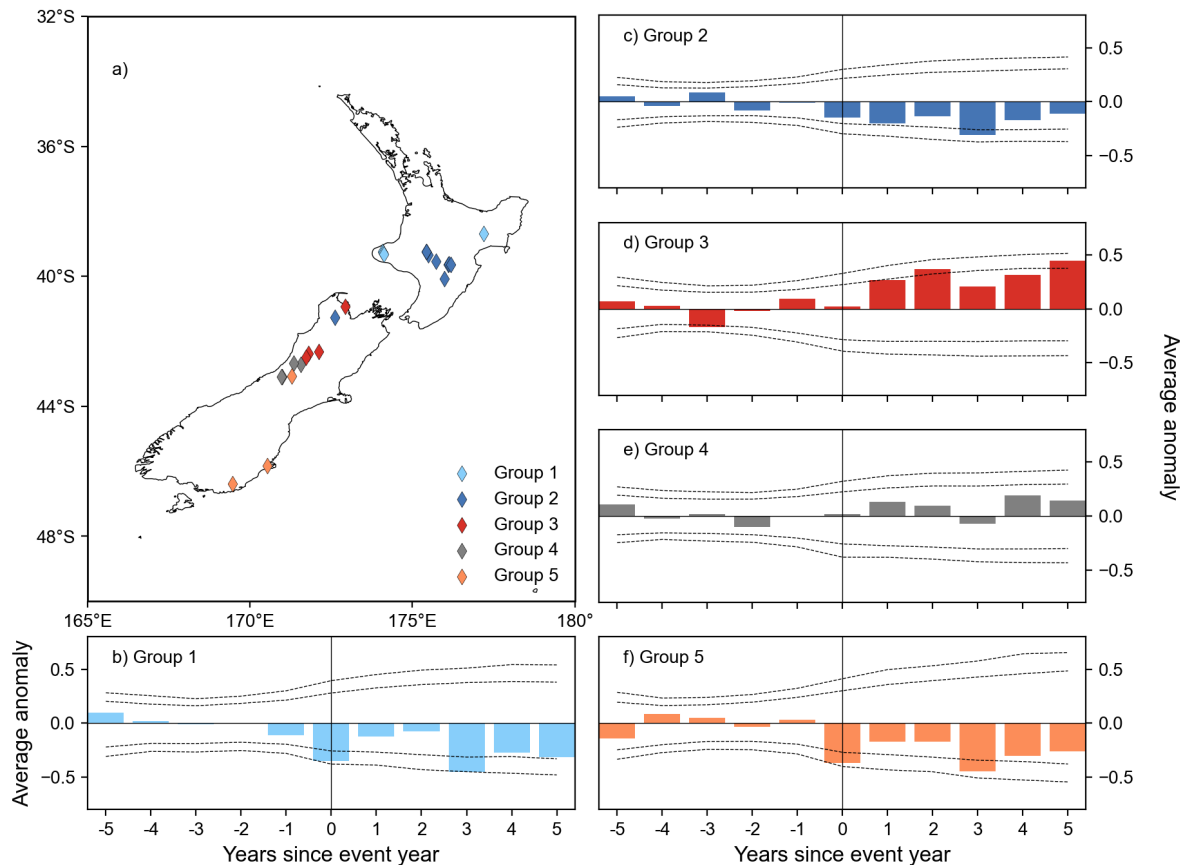
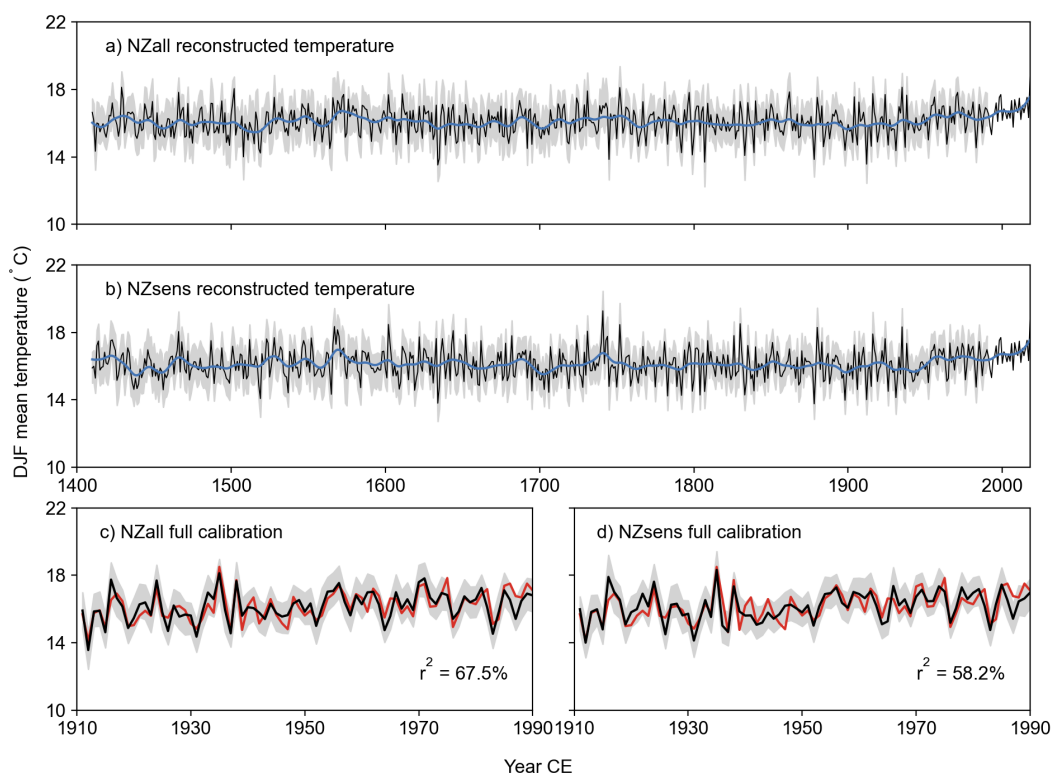



Figure 4 – a) Results of k-means clustering of New Zealand cedar chronologies; b) – f) mean chronology departures five years before and after eruption years (year 0), separated by cluster, and the 95th and 99th significance levels calculated by generating 10,000 random samples of non-event years from the group composite. Map part a) made with Natural Earth free vector map data available at naturalearthdata.com.

3.3 Calibration and validation of the temperature reconstructions

260 The peak summer period was selected as the seasonal reconstruction target, as the largest number of chronologies across species showed significant correlations with temperatures between December and February (Table 1). Selecting only those chronologies correlated at p < 0.1 with average DJF temperatures resulted in a predictor pool of 45 chronologies for reconstruction NZall, of which 25 showed significant volcanic impacts and were used to produce the reconstruction NZsens. Both New Zealand DJF average temperature reconstructions are shown in Figure 5 along with their instrumental fit over the

265 1911-1990 calibration period. There is good agreement between the reconstructions, with a Pearson r of 0.81 over the entire reconstruction period and 0.9 after 1750 CE. The initial, best-replicated nests, which cover the period 1790-1990 CE, account for 67.5% and 58.2% of instrumental temperature variability for the NZall and NZsens reconstructions, respectively. The minimum amount of variance explained over all nests is 44.1% for NZall and 34.3% for NZsens. The full calibration/validation statistics are provided in Supplementary Figures S9 and S10. For both reconstructions, VRE values are positive over all nests

270 from 1413 to 1990, however VCE values are only positive after 1520 CE in the NZsens reconstruction when calibrated to the early window (1911-1950). The declining instrumental data quality in the early period and the relatively few predictors retained for NZsens, are likely responsible for the negative values.

275 **Figure 5 – New Zealand average DJF temperature reconstructions. Unfiltered (black) and filtered (20-year spline; blue) mean DJF reconstruction with 90% uncertainty interval (grey) between 1400 and 2018 CE for a) NZall and b) NZsens. Reconstruction fit to instrumental temperature (red) over the full calibration period 1911-1990 for c) NZall and d) NZsens. The 90% uncertainty interval was calculated from 300 maximum entropy bootstrap replications.**

Increasing temperatures are observable in both reconstructions from around 1950, matching the trend in instrumental temperatures. Prior to the instrumental period, temperatures were higher than average for a sustained period during the 1500s and for a shorter period in the early 1700s. Periods of cooler than average temperatures have also occurred, starting at ~1470, 1630 and 1860 CE. The reconstructions are consistent with previously published temperature reconstructions from New Zealand (Cook et al., 2002; Duncan et al., 2010; Palmer and Xiong, 2004) despite differences in the climate targets (seasons and locations), reconstruction methodologies, and large differences in the number and geographical distribution of chronologies used in their development (Figure S11, Table S5).

3.4 Volcanic signals in the temperature reconstructions

Figure 6 shows the results of the SEA analysis for the two New Zealand temperature reconstructions, for both sets of volcanic events, compared to the volcanic response of an ensemble of seven CMIP5 model outputs for the New Zealand region. For the 21 events with SAOD > 0.04, results are remarkably similar between the temperature reconstructions and the model ensemble. Both the timing and magnitude of the post-event anomaly, which is only significant in year t+1, are consistent across the models and reconstructions, as is the timing of the post-event recovery, which occurs in year t+2. The response to the subset of the 13 largest events shows larger year t+1 temperature anomalies for both the climate models and the reconstructions, with the greatest increase in response magnitude displayed by the model ensemble. Year t+1 anomalies are ~ 0.1 °C larger for NZall, ~ 0.2 °C larger for NZsens, and ~ 0.4 °C larger for the model ensemble than the 21-event anomalies. However, the mean model ensemble lies within the 90% uncertainty range of both reconstructions, indicating that the difference in magnitude between models and reconstructions is not significant for either the restricted 13-event set or the full 21-event set. The difference in post-event recovery is significant, with temperatures recovering by year t+2 in the reconstructions, but modelled temperature anomalies persisting in year t+2. This is the opposite result to many tree-ring based temperature reconstructions from the Northern Hemisphere, which show lagged persistence compared to climate models due to biological effects in the ring-width series (see Discussion 4.3).

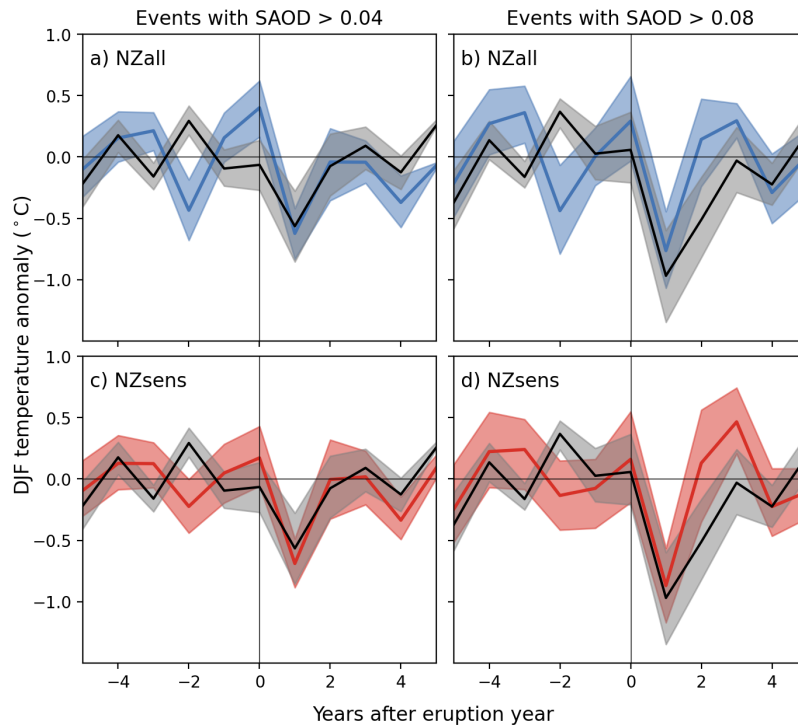



Figure 6 – Mean anomalies five years before and after 21 eruption years with SAOD > 0.04 (left column) and 13 eruption years with SAOD > 0.08 (right column), for both the NZall (blue) and NZsens (red) reconstructions. The mean response from an ensemble of seven climate models to the same set of events is shown in black. The 90th percentile bootstrap confidence intervals were constructed from 1,000 replicates of either 15 or 9 event years at random.

The difference between the NZall and NZsens reconstruction response is minor for both subsets of volcanic events. The anomaly recorded by NZsens is 0.07 °C larger than NZall for the 21-event series and 0.1 °C larger for the 13-event series. The small difference between the reconstructions can be explained by the weightings applied to the chronologies in each reconstruction, with both reconstructions heavily weighted towards the same subset of chronologies. Four of the eight highest-weighted chronologies underpinning NZall are sensitive to volcanic events, and three of these are within the top four highest-weighted chronologies underpinning NZsens (Fig. 7). Thus, limiting NZsens to only sensitive chronologies had less impact on post-eruption temperature anomalies than was expected.

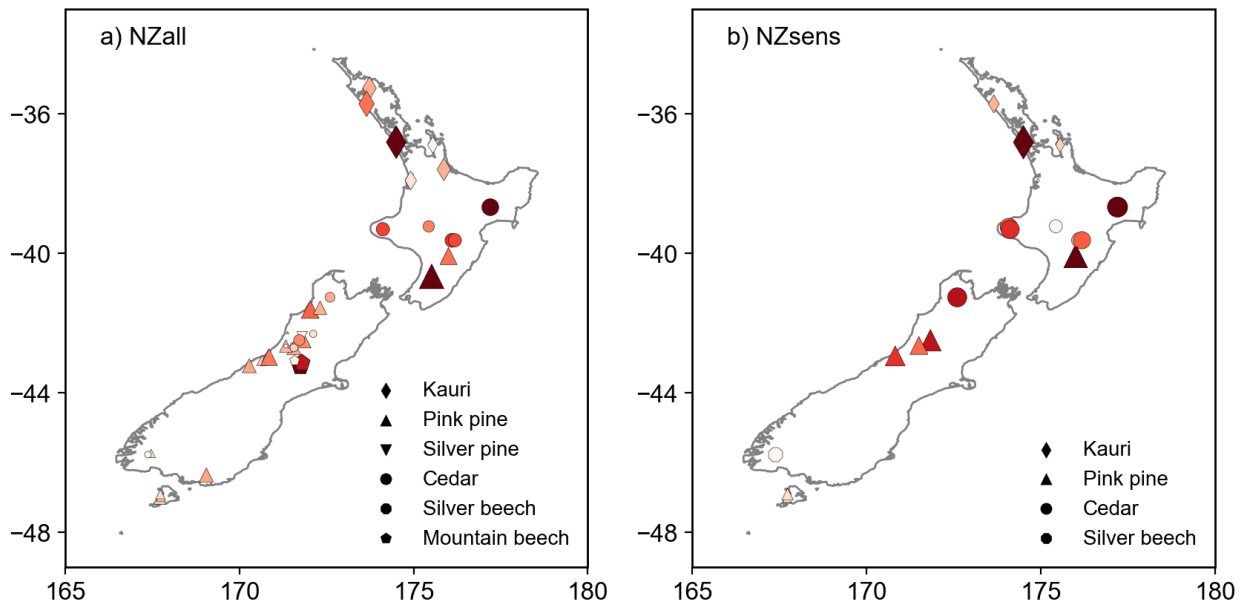



Figure 7 – Distribution of tree rings used in a) the NZall temperature reconstruction and b) the NZsens temperature reconstruction. Larger, darker red markers represent chronologies with greater relative weighting in the multiple regression. Made with Natural Earth free vector map data available at naturalearthdata.com.

4 Discussion

4.1 Volcanic responses recorded by New Zealand trees

Previous studies have not identified significant volcanic responses in Southern Hemisphere tree rings (Krakauer & Randerson, 2003; Palmer & Ogden, 1992) or in the temperature reconstructions based on them (Allen et al., 2018; Cook et al., 1992). In contrast to previous studies, we found that volcanic events can be clearly identified in New Zealand ring widths, although some species are stronger recorders of volcanic signals than others. Unlike Northern Hemisphere high latitude and tree line sites, which tend to show a consistent reduction in growth due to volcanic cooling and reductions in light availability, no consistent response was identified across New Zealand conifer and *Nothofagaceae* species. Predominantly negative (pink pine, cedar, toatoa, silver beech), positive (kauri), and neutral (mountain beech, tanekaha, silver pine) responses were recorded. As most New Zealand chronology sites have been sampled from localised areas of residual forest that are restricted compared to their natural distributional range, it is difficult to distinguish between species-related sensitivities to volcanic eruptions and regional climate factors that may control the response. In reality, it is the combination of biological characteristics including intrinsic species sensitivity, regional climate, and site-specific factors (e.g., soils, exposure to prevailing conditions) which determine the observed volcanic response. While necessarily simplified, here we discuss some possible explanatory factors for the species-wide responses.

The species-level results in Figure 3 and S7 clearly show two response types following volcanic events; a rapid but short-lived response, and a delayed response, which begins in year t+2 or t+3 but then persists over several years. The first response,

335 demonstrated by mountain beech and kauri, we label here the "fast responder", and the second, shown by pink pine, silver pine, cedar, and silver beech, the "stress tolerator" (after Grime (1979)). Many New Zealand conifers appear as typical stress-tolerators, which have adapted to growing in highly stressful conditions. As a group, they are longer-lived, slower-growing, taller, and markedly frost-tolerant compared to endemic angiosperms, and tolerant of poor soils (e.g., low nutrients and often poor drainage). Silver beech is highly frost and exposure resistant, shade tolerant, and grows on extreme exposure sites

340 (Manson, 1974; Stewart, 2002). Several species, including pink pine and silver pine, show an affinity for leached, low-nutrient, and water-logged soils (McGlone et al., 2017). The stress tolerators are characterised by narrow average ring widths and high biological persistence (temporal autocorrelation) arising from carbohydrate storage or leaf retention (see Table 1). Therefore, stress tolerators are slow to respond to changes in conditions, such as volcanic cooling. The stress tolerator response resembles the response of high latitude Northern Hemisphere trees, although arctic trees display even greater lagged persistence, with

345 suppressed growth for up to ten years following volcanic events (Krakauer and Randerson, 2003).

In contrast, the fast responders both respond and recover more quickly from a detrimental change in conditions (e.g., mountain beech) or can rapidly capitalise on beneficial conditions (e.g., kauri). These species are relatively fast-growing, indicated by wider average ring widths than the stress tolerators, and have lower persistence (Table 1). Mountain beech is shade intolerant but has several responses to abnormally cold temperatures, including rapid shoot growth and temporarily halting bud

350 formation, which allows it to rebound quickly after a poor summer (Wardle, 1970). Kauri could be considered a stress tolerator due to its affinity for poor soils, occurrence on ridges and slopes, and drought tolerance (McGlone et al., 2017); however, relative to other New Zealand conifers in this study, it is a fast responder.

In contrast to the subdued, persistent decrease in growth shown by the stress tolerator species, the initial decline in toatoa ring width in year t+0, then subsequent extreme decline in year t+3 and recovery by year t+4 closely resembles the boom-bust

355 behaviour of the fast responders, but with several years' lag. The dominant climate response of toatoa is a weak negative correlation to prior growing season temperatures (Fig. S6a) but a strong positive correlation to summer temperatures two growing seasons prior. This results in a quasi-biennial pattern of wide and narrow rings, which has also been observed in other species of *Phyllocladacae*. This pattern may be related to a climate-triggered flowering cycle (Ogden and Dunwiddie, 1982; Allen, 1998), foliage production followed by cladode senescence, or a mast seeding event, which can be triggered by multiple

360 cool summers in New Zealand *Podocarpaceae* (Norton and Kelly, 1988). All three potential explanations suggest toatoa channels resources to reproduction at the expense of cambial growth (Harper, 1977) following a climate trigger after volcanic events - perhaps increased humidity and reduced summer water stress at low elevation North Island sites, or an increase in photosynthesis due to a greater fraction of diffuse radiation. More research on the ecology and life history of toatoa is needed to confirm these possible mechanisms.

365 We compared the response at six sites which each have chronologies from two different species (Fig. S8) providing the unique opportunity to compare species differences in volcanic sensitivity directly whilst controlling for most other factors. The three species which are collocated and thus available for site-based comparison (cedar/pink pine and cedar/silver pine) all showed stress tolerator responses to volcanic eruptions. Pink pine and cedar often grow together in mixed stands. Both species are

sensitive to temperature, although pink pine has a maximum correlation to late summer temperature, whereas cedar responds

370   to conditions in the winter prior to the growing season and in spring (Fenwick, 2003). A significant difference in the response between species was observed only at one of three sites. Comparison over additional sites is therefore required to determine whether the difference in seasonal temperature response may result in a difference in the sensitivity of pink pine and cedar to climate disturbance following eruptions. Differences between the cedar and silver pine responses were observed at two of the three sites, with cedar showing greater sensitivity to volcanic eruptions. Silver pine is primarily found in the moist, temperate,

375   low-elevation forests of the west coast of the South Island. It is a shade-tolerant species that grows in highly competitive closed-canopy forests on infertile, poorly drained or water-logged soils (Wardle, 1977; Cook et al., 2002). It is exceptionally slow-growing and shows little year-to-year variability in ring width (Table 1). Thus, it is unsurprising that volcanic effects were more readily identified in cedar at the Ahaura and Flagstaff Creek sites (Fig. S8).

4.2 A Kauri growth benefit

380   An interesting result of this study is the strong positive species-wide response of North Island kauri to volcanic events (Fig. 3a) despite the weak correlation of the chronologies to monthly temperatures (Fig. S3). Over 70% of the kauri chronologies recorded a small but significant increase in ring width in the year following a large eruption (SAOD > 0.04), indicating a growth benefit from volcanism. Previous studies of kauri climate-response function have shown that growth is not primarily related to temperature but is enhanced during cool, dry years, with the strongest (negative) correlation to austral spring

385   temperatures (Ogden and Ahmed, 1989; Buckley et al., 2000). Ring growth is thus enhanced during El Niño events, which result in cool, dry spring conditions in northern New Zealand, and kauri has been successfully used as a proxy for the El Niño-Southern Oscillation (Fowler et al., 2008). The mechanism behind this relationship remains largely unclear, although it has been proposed that reduced cloud cover during El Niño events may benefit kauri growth via increased insolation (Fowler et al., 2000). The opposite conditions follow a volcanic eruption, with reduced direct insolation and increased diffuse insolation

390   due to scattering by volcanic aerosols (Gu et al., 2003). The commonality between the two sets of events is cooler-than-average spring/summer temperatures.

This suggests that kauri may capitalise on a decrease in summer evapotranspiration during both El Niño events and following significant eruptions. Maximum kauri growth occurs during spring, with large declines in growth rate over the peak summer months when evapotranspiration exceeds precipitation in the northern North Island (Fowler et al., 2005). Dendrometer band

395   studies suggest that reduced spring/summer moisture stress may delay the cessation of growth, resulting in wider annual rings (Palmer and Ogden, 1983). No summer cessation of growth was observed by Palmer & Ogden (1983) at the highest altitude site, Mt Moehau (1MOE, Table S1). This site receives moisture from condensation and fog drip as well as rainfall, reducing the summer precipitation deficit. Plausibly, the increase in diffuse radiation and resulting enhanced photosynthesis (Gu et al., 2003; Robock, 2005) may also contribute to post-event kauri growth. However, tree growth is generally more constrained by

400   the environment than photosynthesis (Fatichi et al., 2019; Zweifel et al., 2021), so increased photosynthesis may not necessarily translate into growth (i.e., a wider ring) in the presence of another limiting factor, such as the summer moisture deficit.

Additional research is needed to understand the relative importance of temperature, light availability, humidity, and soil moisture to sub-annual growth in kauri.

Many observational and modelling studies propose a link between large tropical volcanic eruptions and sea surface temperature variability in the tropical Pacific, with El Niño-like conditions more likely in the year following a significant event (Emile-Geay et al., 2008; Adams et al., 2003; Khodri et al., 2017; Christiansen, 2008; Miao et al., 2018; McGregor et al., 2010), although this link is not always identifiable in the paleoclimate data (Dee et al., 2020). The three eruptions included in this analysis since 1900 co-occurred with an El Niño event, and the 1982/83 El Niño is one of the largest on record (Santoso et al., 2017). While we do not wish to debate the eruption-ENSO response as part of this study, these potential interactions complicate our analysis of the volcanic signal in kauri.

In an attempt to distinguish between the effects of El Niño events and volcanic eruptions on kauri growth, we repeated the SEA analysis, removing the three volcanic eruptions since 1900. A smaller composite ring-width anomaly was recorded without the three events, but the response remained significant in year t+1 (Fig. S13). To test the potential follow-through impact of the kauri response to El Niño events on the temperature reconstructions, we removed the ENSO component via linear regression of the Southern Oscillation Index on the reconstructed temperature series. There is a negligible difference between the original and ENSO-adjusted temperature reconstructions for all volcanic events between 1880 and 1990 CE, except for the response to El Chichón in 1982, which is much larger in the unadjusted reconstruction (Fig. S14). Based on currently available data, we cannot confidently discount that the kauri growth benefit identified in year t+1 may be a secondary response to changes in tropical Pacific sea-surface temperatures following a large eruption. However, this is unlikely to have a large impact on the post-event anomalies identified in the temperature reconstructions.

4.3 Site-related volcanic responses

Differences in volcanic response between sites are observed for all species, largely between sites with significant decreases in growth and sites with neutral responses (Fig. 3, Fig. S7). More temperature-limited sites, such as sites at higher elevation and lower latitude, are expected to be more sensitive to volcanic cooling and thus experience the most reduction in growth. Broadly in line with this expectation, chronologies that are highly correlated to monthly temperatures show greater sensitivity to volcanic eruptions (Fig. S15). However, there are many exceptions, both for temperature-sensitive sites with a neutral volcanic response, and sites that are only weakly correlated to temperature but are markedly affected by the climatic changes following volcanic eruptions. Thus, volcanic response cannot be simply interpreted as a response to cooler-than-average temperatures.

Based on the variability in volcanic response observed in cedar (Fig. S8) it is evident that site-related factors can have a substantial impact on the volcanic response within a species group. This finding was further explored using k-means clustering of the widely distributed cedar chronologies (Fig. 4). Altitude and latitude are expected to be important explanatory factors for cedar tree growth, as together they represent the relative importance of temperature and water stress at a site. Temperature-limited high-altitude cedar sites at or near the treeline in the North Island ranges show a significant decline in tree growth following eruptions, as did coastal sites at higher latitudes (~ 46 ºS). We observed a significant increase in cedar growth at

435 low-elevation sites on the northern South Island (Group 3) in response to volcanic cooling, which we interpret as a reduction in summer evaporative demand. Low-elevation trees are more likely to experience summer water stress than their high-elevation counterparts due to higher average temperatures if precipitation rates are similar. In contrast to the significant positive correlation of treeline cedar sites to average summer temperatures (Figure S5), the Group 3 chronologies display a negative correlation to summer temperatures (not significant at $p < 0.05$) indicating that soil moisture may be a limiting factor at these

440 sites. Thus, we find that both high and low-elevation cedar stands can reliably record volcanic signals, provided that the sites experience sufficient temperature or moisture stress. Sites that are neither strongly temperature nor water limited (Group 4; Fig. 4) show a neutral response to volcanic eruptions. A limitation of this analysis is that we have not considered potential spatial differences in the regional pattern of cooling or changes in regional atmospheric circulation patterns (Salinger, 1998) which could also impact the results for species with a wide distributional range, like cedar.

445 Tree growth of species at different sites is limited by a variety of environmental factors, of which temperature and soil moisture are only two (Fritts, 1976). For many New Zealand species, little is known about what types of sites might accentuate these factors and thereby enhance the climatic sensitivity in the tree-ring series (Dunwiddie, 1979). Although the overall Group 2 cedar response was significant, not all high-altitude sites recorded a volcanic signal. Considering the location, aspect, forest characteristics, and soil type at individual cedar sites, we find that exposure to prevailing conditions is the key explanatory

450 variable for the within-species response for sites near the altitudinal limit. Sites that record a significant growth response have high exposure to prevailing winds and are more sensitive to abnormally low growing season temperatures. In contrast, chronologies from sites characterised by undulating ridgelines and more continuous forest showed a neutral growth response. Sites experiencing mesic conditions and closed canopy forests tend to show lower sensitivity to adverse environmental conditions, such as low temperature (Phipps, 1982). Closed canopy forests are also more likely to be sensitive to increases in

455 the fraction of diffuse radiation driving photosynthesis (Gu et al., 2003; Tingley et al., 2014) and thus, the increase in diffuse radiation fraction may compensate for the decrease in temperature to a greater extent compared to sites with more open canopies.

North Island kauri is another species for which exposure appears to be a determining factor in the chronology response to eruptions. For kauri, sites with a strong positive response to volcanic eruptions are coastal sites exposed to prevailing wind

460 conditions or sites limited by poor underlying sediment substrates (e.g., 1TRO, 1KAW; Table S1). In comparison, sites that showed little volcanic response were those on the leeward side of the coastal range, which are buffered by inland microclimate effects (e.g., 1PBL, 1PKF; Table S1). These sites likely experience less water stress during the summer; therefore, we expect they receive less benefit from volcanic cooling reduced evaporative demand, resulting in a neutral response. The importance of aspect to climate sensitivity - particularly when windward sites are exposed to prevailing winds - has been highlighted in

465 many previous studies (e.g., Dang et al., 2007; Rozas et al., 2013). For New Zealand, a thorough exploration of the importance of site-based parameters other than elevation and latitude (e.g., aspect, exposure, soil type) to volcanic sensitivity is limited because these parameters have not been recorded for many sites.

4.4 Implications for temperature reconstructions

470 We expected to find a substantially greater volcanic response in NZsens (i.e., limited to only those chronologies with an individual significant volcanic response), compared to NZall. However, while NZsens shows a larger post-volcanic temperature response, the difference between the two reconstructions is not significant (Fig. 6). As shown in Figure 7, both reconstructions are heavily weighted towards the same subset of chronologies. Since, in general, sites with higher sensitivity (correlation) to temperature show higher volcanic response (Fig. S15), limiting NZsens to only sensitive chronologies has only

475 a small impact on post-eruption temperatures. Another factor leading to the minimal difference between the reconstructions is that many volcanically sensitive chronologies, particularly kauri, were cored before 1990 and therefore not included in either temperature reconstruction. These sites should be updated with priority for future studies of volcanic impact in the Southern Hemisphere. In developing NZsens, we used a "volcanic sensitivity" threshold based on the SEA result significance ($p < 0.05$). By doing so, we reduced the size of the predictor pool, which reduced the strength of the reconstruction, particularly over the

480 initial 100 years, when there were relatively few predictors (Fig. S10a).

When testing the reconstructions using the event list from Toohey & Sigl (2017) (Fig. 6) we concluded that losing reconstruction strength outweighs the small increase in volcanic sensitivity in NZsens and that it is not beneficial to restrict the predictor pool. However, when we then repeated the SEA analysis using the event list derived from Crowley & Unterman (2013), the mean response of NZall to the largest subset of 12 events with SAOD > 0.08 (Table S3; Fig. S12c) was not

485 significant ($p > 0.05$). The benefit of the restricted predictor set in strengthening the volcanic signal in NZsens is highlighted when using this event list. It is important to note that the mean NZall response to the full set of Crowley & Unterman (2013) events with Southern Hemisphere-average SAOD > 0.04 is significant (Fig. S12a), which suggests that some eruptions classified as SAOD > 0.08 in Table S3 were not climatically effective over New Zealand. Potential reasons for the differences between the two volcanic data sets, which may have impacted the findings here, are discussed in Toohey & Sigl (2017).

490 Figure S12c indicates that the SEA compositing procedure can fail when using a small number of events if the volcanic signal is small compared to other sources of interannual variability, especially when not all events have a climate impact. This is one potential reason this study has identified significant volcanic signals in Southern Hemisphere tree rings when previous studies did not. Before Gao et al. (2008), no comprehensive reconstruction of global aerosol loading was available. Uncertainty in eruption dates/sizes likely contributed to the lack of volcanic signal identified in studies undertaken prior to the release of the

495 'Gao' dataset (e.g., Cook et al., 2002; Villalba and Boninsegna, 1992). Revisiting the data from other major Southern Hemisphere dendrochronology regions (e.g., Tasmania, South America) is therefore an important aspect for future research. Previous studies narrowly focussed on the impacts of the 1815 C.E. eruption of Tambora on New Zealand tree rings (Palmer and Ogden, 1992; Norton, 1992) also presented inconclusive results. The authors of these studies were seeking synchronous growth reductions across species, whereas our analysis, with the benefit of much more data, shows responses vary widely

500 between species. Because of this variation in response, studies that rely on compositing across species and regions (e.g., Krakauer & Randerson, 2003) are also likely to underestimate the true volcanic response in Southern Hemisphere tree rings.

In this study we also compared reconstructed temperature anomalies with anomalies from climate models over the New Zealand region for DJF - peak growing season in the Southern Hemisphere. We found no difference between the magnitude of the year t+1 anomaly for either the 13- or 21-event composites, with the difference between the reconstructed and modelled anomalies < 0.12 ºC for both sets of events. Recent work investigating the reasons for differences between climate model and proxy reconstructions of post-event temperature anomalies in the Northern Hemisphere (Zhu et al., 2020) found that these differences can be minimised by focussing on the growing season rather than annual temperatures, undertaking regional rather than hemispheric analysis, and resolving biological persistence. By focusing on regional DJF temperatures, we resolved two of these issues. A criticism of temperature reconstructions based solely on ring widths is that biological persistence in treeline conifers decreases the abruptness and magnitude of volcanic cooling. In the Northern Hemisphere, more emphasis is now being placed on maximum latewood density (MXD) or mixed MXD and ring widths for investigations of volcanic cooling (Wilson et al., 2016; Zhu et al., 2020). For this study, we focussed only on ring widths, as few investigations of alternative wood properties have been undertaken in New Zealand (Blake et al., 2020; Xiong et al., 1998).

Unlike some Northern Hemisphere studies, our ring-width temperature reconstructions show no increased persistence in temperature anomalies following eruptive events compared to the climate model ensemble (Fig. 6). Ring widths from New Zealand conifers therefore appear suitable for volcanic investigations. Northern Hemisphere high altitude/latitude trees predominantly used to determine the temperature impacts of volcanic eruptions contain higher biological persistence than the chronologies we used in our temperature reconstructions, influencing their post-eruption response. For example, the average first-order autocorrelation of our predictor chronologies is 0.53 (range 0.15-0.87; SD 0.15) compared to Arctic sites with an average of 0.62 (range 0.15-0.93; SD 0.13; (Cropper and Fritts, 1981)). Nevertheless, several New Zealand species do show lagged volcanic response (Fig. 3, Fig. S7) which is not present in the final temperature reconstructions. Methodological decisions play an important role in the persistence of tree-ring based temperature reconstructions (Büntgen et al., 2021). In our reconstructions, pre-whitening of both the tree-ring predictors and the temperature data, including significant lagged predictors, and the selection of predictors from multiple species all contribute to the responses we identified.

5   Conclusions

Very few studies have considered whether volcanic signals are identifiable in tree-ring chronologies from the Southern Hemisphere. We investigated whether volcanic events could be identified in New Zealand tree rings, using data from eight dendrochronological species. In doing so, we set out to answer three questions: 1) can volcanic signals be identified in the Southern Hemisphere?, 2) are there species-level differences in volcanic signal strength?, and 3) does chronology selection impact the magnitude of post-volcanic cooling in temperature reconstructions from tree rings?

In answering the first two questions, we found that New Zealand dendrochronological species are reliable recorders of volcanic cooling, but that response varies across species. The magnitude and persistence of the species-wide volcanic response can be broadly linked to plant life history traits. The larger magnitude and more immediate responses are recorded by the "fast responder" species, such as mountain beech and kauri, and more delayed but persistent responses are recorded by the "stress

tolerator" species, such as silver pine. In general, volcanic events can be more readily observed in the ring widths of fast responder species, which should be prioritised for future regional or hemispheric studies. Unfortunately, the paucity of information on the ecology of many New Zealand species limits our understanding of how species allocate resources to processes other than cambial growth in response to short-term changes in climatic conditions.

The volcanic response of New Zealand trees is complex, with positive, negative, and neutral responses identified sometimes within the same species group. For sub-alpine sites, this finding is not dissimilar to previous studies of temperate zone Northern Hemisphere species. We found that site-related factors have greater control over displayed volcanic responses than species and presented a suite of plausible, testable hypotheses explaining the results. The altitude of the site with respect to the species altitudinal limit, and exposure to prevailing conditions, are factors thought to determine whether a tree-ring volcanic response could be identified. In some cases, sites near the lower altitudinal limit of the species were also strong responders, suggesting a reduction in summer moisture stress could also be an important factor in post-volcanic growth. Our results indicate that studies intending to utilise tree rings to investigate regional volcanic cooling should carefully consider the characteristics of the sample site. While valid for all dendrochronological studies, it is particularly important for identifying volcanic signals, as we find that the range of temperature-sensitive sites is greater than the range of volcanically sensitive sites.

In answer to the last question, we developed two new reconstructions of New Zealand summer temperature to investigate whether chronology selection impacted the magnitude of post-volcanic cooling. There was little difference in the post-event anomalies, suggesting limiting the predictor pool for volcanic sensitivity is unnecessary when targeting average growing season temperatures in New Zealand. Both reconstructions showed temperature anomalies remarkably consistent with studies based on instrumental temperature, and with the ensemble mean response of CMIP5 climate models. Based on these results, New Zealand ring widths are reliable indicators of regional volcanic climate response.

More broadly, the findings of this study have important implications for the development of future tree-ring or multiproxy hemispheric temperature reconstructions from the Southern Hemisphere, which often incorporate species-specific "master" chronologies (i.e., composite chronologies developed from across many sites) into their predictor pool. As shown in this study, the compositing process can result in reduced volcanic signals when more than one type of response (i.e., positive, negative, or neutral) is recorded by a single species. However, as most New Zealand species-level composites show significant volcanic responses, temperature reconstructions based on composite chronologies should also show the influence of volcanic eruptions.

Competing interests

The authors declare that they have no competing financial interests.

Author contribution

PAH and JGP conceptualised this study, JGP curated the data and PAH undertook the analysis. PAH wrote the manuscript with contributions from all authors.

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Data availability statement

All data and software used in this study are publicly available. The New Zealand 'seven station' temperature series was
580 downloaded from NIWA at https://niwa.co.nz/. CMIP5 climate model outputs were downloaded from https://esgf-node.llnl.gov/projects/cmip5/. The Southern Oscillation Index time series was sourced from https://www.ncei.noaa.gov/. The raw tree-ring width series can be downloaded from the International Tree Ring Data Bank at https://www.ncei.noaa.gov/. Superposed epoch analysis was undertaken using R code published on Mendeley Datasets with DOI 10.17632/8p7y29hz5h.1. The two new temperature reconstruction series can be accessed through the NOAA/World Data Service for Paleoclimatology
585 archives (https://www.ncdc. noaa.gov).

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