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A framework for testing radiata pine under projected climate change in Australia and New Zealand

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Abstract Radiata pine plantation resources in Australia and New Zealand are a highly productive source of solid-wood and pulp products for domestic consumption and export. This has largely been achieved through long-term investments in tree breeding programs that select the best-performing genotypes for varied regional environments. However, climate change could threaten the realisation of genetic improvement in plantations due to suboptimal matching of improved planting stock to new climate conditions. Here, we investigate how information from genetic field tests could be utilised under anticipated climate change. We use principal component analysis and Mahalanobis distance measures to find the closest match between climate of plantation regions in the future and current climate of field test sites. By 2050, future climates of some important plantation regions are expected to match climates currently present in different regions. For example, future climates of Green Triangle, a key plantation region in Australia, will better match current climate of Western Australia. The Central North Island of New Zealand will shift to warmer and wetter climate with no current analogue, and Western Australia, to warmer and drier no-analogue climate. The latter is also likely to fall outside the climate niche where

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radiata pine can be grown in the future. Nevertheless, for the majority of radiata pine plantation regions in Australia and New Zealand our analysis provides a framework of how anticipated climate change can be addressed in tree improvement programs using existing field tests.

Keywords *Pinus radiata* · Climate change · Plantation forestry · Tree breeding · Adaptation strategies · Australia · New Zealand

Introduction

Radiata pine (*Pinus radiata* D. Don) is the most important introduced forest tree species in Australia and New Zealand. Commercial plantations of radiata pine supply more than 50 % of raw material for the forest industry in Australia (ABARES 2014) and 90 % in New Zealand (MAF 2014). The high productivity of radiata pine plantations has largely been achieved through long-term investments in tree breeding programs with an estimated 30 % genetic gain in volume having been achieved since the 1950s (Wu and Matheson 2005).

Radiata pine originates from a narrow coastal range in California with three disjoint populations within an approximately 200 km coastal range: a northern population in Año Nuevo state park, the largest population around the town of Monterey, and a small third population near the village of Cambria in the south. The climate conditions within the native distribution are mild Mediterranean conditions with a strong maritime influence. Mean annual temperatures range from 12 to 13 °C, with monthly average minimum temperatures of 6 °C in winter to monthly average maximum temperatures of 20 °C in summer. Rainfall averages 400–900 mm per year, but can vary greatly from year to year. Up to 80 percent of annual precipitation falls in the winter. Summers are dry, but summer fog drip can reach 15 mm per week. There is no snow fall in the natural range of radiata pine.

In contrast to the narrow climatic range of its origin, radiata pine plantations have been established in Australia and New Zealand under a wide variety of climatic conditions. In southeast Australia radiata pine has proven productive under Mediterranean climate similar to its climate of origin. Climates of the northeastern New South Wales plantation regions are differentiated by higher summer rainfall, and Western Australian planting regions have substantially higher temperatures and a prolonged dry summer periods relative to their native range. Plantations in Tasmania are characterized by substantially colder climates and high precipitation (~1000 mm), whereas in New Zealand precipitation may be very high (typically 1500–2000 mm), while mean annual temperatures range from 9 °C with regular snow and frost periods in southern regions to 16 °C with subtropical conditions on the North Island (Mead 2013).

Radiata pine breeding populations in Australia are based on land races derived mainly from provenances sourced from Monterey, while New Zealand populations primarily originate from the native Año Nuevo populations (Wu and Matheson 2005). In both Australia and New Zealand, radiata pine selected in regional breeding programs are now in advanced breeding generations (typically the 4th generation) and therefore the adaptive characteristics of the original provenances can be expected to be highly modified (e.g. Espinoza et al. 2014), resulting in significant genotype by environment interactions (G × E) among families in breeding programs (Wu and Matheson 2005; Raymond 2011; Gapare et al. 2012).

Although strong G × E in the performance of the original provenances Año Nuevo, Monterey, and Cambria is no longer present in breeding population (Gapare et al. 2015), several studies point to significant G × E that is primarily attributable to temperature (or elevation) gradients (Wu and Matheson 2005; Raymond 2011) and in some cases can also be linked to precipitation differences among planting sites (Gapare et al. 2015; Ivković et al. 2015). Nevertheless, all studies agree that temperature is the most important driver of G × E in radiata pine breeding populations, and Wu and Matheson (2005) were the first to advocate the use of high and low-elevation breeding populations that would allow for doubling the genetic gain over a single population for their test series in Australia. Similarly, a substantial (approx. 20 %) genetic gain for diameter at breast height was predicted for New Zealand with separate breeding populations for cold southern and high elevation environments (Gapare et al. 2015).

Genotype by environment interactions among genotypes within breeding populations that can be attributed to climatic drivers also raise concerns regarding the deployment of well-adapted planting stock under climate change. Radiata pine plantation areas are unlikely to shift due to landholding arrangements, and the next generation plantations needs to be established with genetic stock that is well adapted to anticipated future climate conditions while also surviving current plantation environments (Pinkard et al. 2014). Human intervention may be required to help forests adapt to new environmental conditions created due to climate change (e.g., Gray et al. 2011; Pedlar et al. 2012), and in some cases changes to what seed sources and genotypes are used in reforestation programs have already be implemented to address climate change (e.g. O'Neill et al. 2008).

The recent State of the Climate Report by Bureau of Meteorology and CSIRO (2014) reported that Australia's mean annual temperature has warmed by 0.9 °C since 1910, and that frequency of extreme weather has changed, with more extreme heat and fewer cool extremes. Australian temperatures are projected to continue to increase, with more extremely hot days and fewer extremely cool days. Autumn and early winter rainfall has mostly been below average in the southeast since 1990 and average rainfall in southern Australia is projected to decrease. In New Zealand, observed trends are less pronounced, but projected changes are still substantial from a forestry perspective. Based on the projections by the IPCC (2013), temperature is expected to increase throughout the country. For example, mean monthly temperature in New Zealand's Central North Island, one of the largest contiguous exotic plantation areas in the world, is likely to be at least 0.9 °C warmer by 2040 and 2.1 °C warmer by 2090 in mean annual temperature, compared to 1990, with about 30–60 extra days exceeding 25 °C and 20 fewer frosts per year. Rainfall is expected to decrease throughout most of the North Island and northern South Island but to increase in West Coast, Otago, and Southland.

The objective of this study was to investigate how information from long-term genetic field tests represents plantation regions under anticipated climate change, and how the information can be applied to new plantings of radiata pine in Australia and New Zealand. Our specific objectives were to (1) examine how well existing genetic field tests represent climate conditions of radiata pine plantations in Australia and New Zealand under current climate; (2) match existing genetic field tests to plantation regions under anticipated future climate conditions, so that valuable existing genetic information can be used for appropriate deployment to plantation regions; (3) identify gaps of underrepresented climate habitat where field tests should be currently planted so that they can be used to select appropriate genotypes in the future, and (4) identify no-analogue climate conditions where future deployment of radiata pine in Australia and New Zealand may be uncertain.

Methods

Plantation and test site data

In Australia radiata pine is planted on 773,000 ha or approximately 75 % of the total softwood plantation area. Radiata pine is planted in 11 National Plantation Inventory (NPI) regions, which are based on industry wood supply regions (Gavran 2014): Western Australia (WA), Mount Lofty Ranges and Kangaroo Island (ML), Green Triangle (GT), Northern Tablelands (NT), Central Tablelands (CT), Southern Tablelands (ST), Murray Valley (MV), Central Victoria (CV) and Central Gippsland (CG), Bombala-East Gippsland (EGB) and Tasmania (TAS), (Gavran 2014). The two largest NPI regions are the Murray Valley (185.600 ha) and Green Triangle (176.300 ha) (Fig. 1). New Zealand has about 1.5 million ha of radiata pine plantations (MAF, 2014). The following nine wood supply regions were evaluated: Northland (NL), Central North Island (CNI), East Coast (EC), Hawke's Bay (HB), Southern North Island (SNI), Nelson-Marlborough (NM), Canterbury (CAN), West Coast (WC) and Otago-Southland (OS) (Fig. 1).The majority of radiata pine plantations are in the CNI wood-supply region (521.000 ha), which comprises for 31 % of total plantation area, compared with 25 % in the entire South Island (MAF 2014).

The climatic characterization of radiata pine plantation regions in Australia were based on spatial data obtained from Department of Agriculture (2010). The layers consisted of polygons, accurate at a map-scale of 1:2,000,000. Spatial layers of radiata pine plantations in New Zealand were obtained from Land Resource Information Systems Portal (LRIS 2014) website for exotic forest in New Zealand. The data describe various aspects of New Zealand's climate, landforms and soils. Polygon data of radiata pine plantations were rasterized to the same resolution as the gridded climate data layers, and then regional estimates of climate conditions were calculated as averages across grid cells. The climatic characterization of genetic field tests of radiata pine was based on geographic coordinates for 306 Australian and 114 New Zealand tests that comprehensively cover effort in genetic tree improvement. Those tests have measurements data stored in the DATAPLAN® data management system of the Southern Tree Breeding Association (STBA) in Australia, and exSITEz® data management system of Radiata Pine Breeding Company (RPBC) in New Zealand.

Climate data

Current climate layers and future projections were obtained from the WorldClim v1.4, Release 3 (Hijmans et al. 2005). WorldClim is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometre (30 arcseconds). The data available were climate projections from 18 global climate models for four representative CO_2 concentration pathways (RCPs). These are the most recent climate projections associated with the 5th Assessment Report of the Intergovernmental Panel for Climate Change (IPCC 2013). We used projections for the 2050s to represent a medium-term time horizon in a forestry context. The projections were based on a median emission scenario RCP 4.5.

The representation of current climate in WordClim is for the 1951–2000 period. We performed an adjustment by subtracting the difference of the 1951–2000 period from the 1961–1990 period using the CRU-TS v3.2 monthly dataset (Mitchell and Jones 2005) to obtain the widely used 1961–1990 long-term climate reference period, and to match climate conditions where most field tests were grown and evaluated. We also analysed

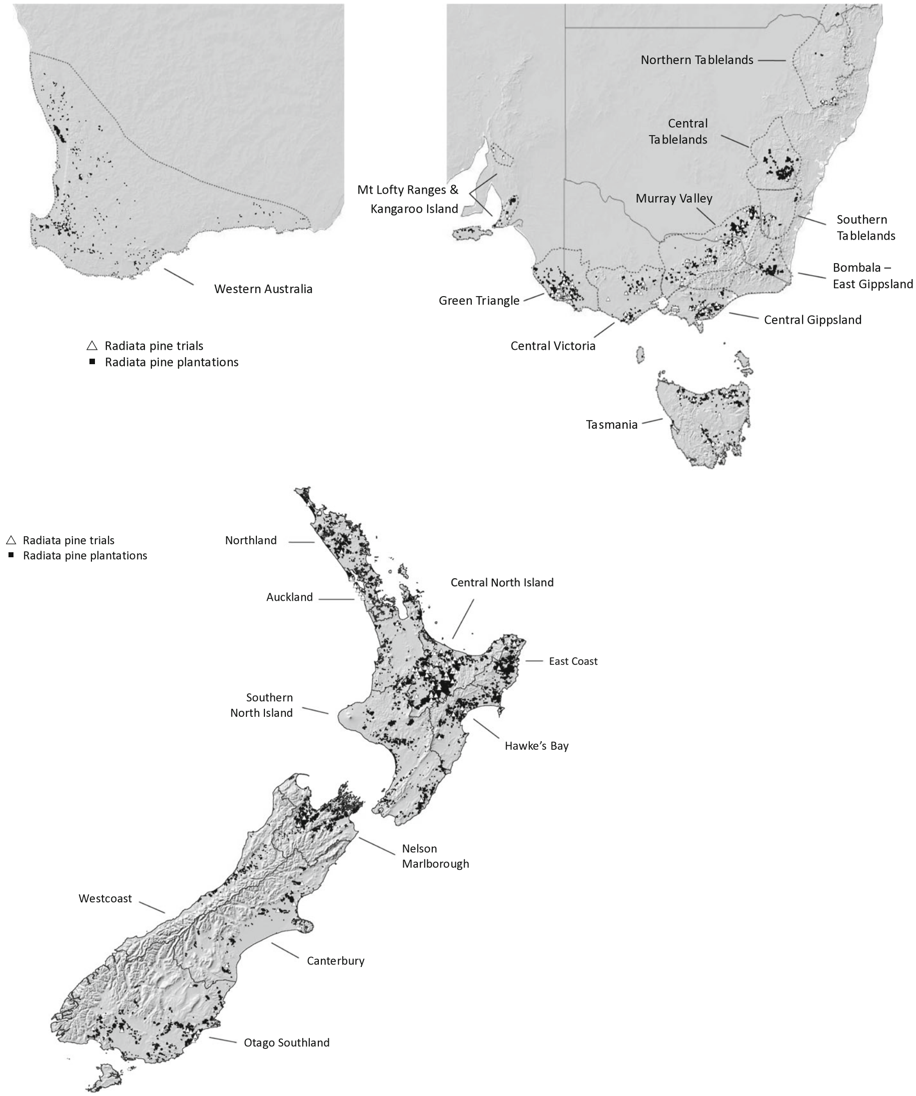

Fig. 1 Plantation regions for Australia and New Zealand

observed climate trends for the study regions using the same historical CRU-TS v3.2 dataset, where we visualize climate trends as the difference between the 1961–1990 climate normal and a recent 15-year average period from 1995 to 2009. The difference between these two periods represent an approximately 25-year climate trend (i.e. the time between the midpoints 1976 and 2002 of the two periods). Using a shorter 15-year average (1995–2009) to represent climate change is a compromise between accurately representing recent climate trends and the hazard of interpreting cyclical or random variability as a directional trend.

For our analyses, we calculated eight biologically relevant climate variables, including mean annual temperature (MAT), mean maximum temperature of the warmest month

Table 1 Range of climatic environments where radiata pine is grown as an important forestry species in Australia and New Zealand

Region (abbreviation)	MAT	TD	Min TCM	Max TWM	MAP	PGS	ACMD	SCMD
Australia								
Western Australia	16.4	11.1	6.7	29.7	792	97	−29.1	−35.3
Mt. Lofty Kangaroo Isl.	14.3	10.7	5.4	26.2	728	140	−15.7	−25.0
Green Triangle	13.7	9.5	5.1	25.2	744	172	−8.4	−20.7
Central Victoria	12.2	11.0	3.3	24.4	956	280	18.5	−14.1
Central Gippsland	12.8	10.3	3.0	24.1	877	330	8.0	−9.9
Murray Valley	12.2	15.1	0.2	27.7	1104	327	16.7	−20.7
Bombala-East Gippsland	11.0	11.8	0.0	23.3	825	382	5.5	−7.8
Southern Tablelands	12.0	14.2	−0.6	26.4	852	358	−5.6	−15.3
Central Tablelands	10.9	13.6	−0.4	24.5	974	411	16.3	−6.0
Northern Tablelands	12.5	13.2	−0.3	25.0	973	499	2.7	−0.3
Tasmania	10.8	9.1	2.5	21.0	1080	330	45.0	−4.1
New Zealand								
Northland	15.1	8.6	7.4	23.9	1514	507	77.2	5.5
Central North Island	12.1	10.3	2.6	22.6	1658	636	94.8	12.7
East Coast	12.5	10.0	3.1	23.0	1800	621	106.0	9.2
Hawke's Bay	12.1	10.4	2.5	22.7	1556	588	83.5	9.7
Southern North Island	11.9	9.7	3.1	21.9	1407	498	74.3	6.0
Nelson Marlborough	11.0	10.0	1.4	20.7	1423	520	81.0	8.3
West Coast	11.4	9.4	2.3	20.3	3359	1375	276.5	59.4
Canterbury	10.1	10.9	0.2	20.4	871	347	27.8	−1.5
Otago Southland	9.0	10.6	−0.5	19.3	960	410	41.8	4.7

Plantation regions are shown in Fig. 1

(MaxTWM), mean minimum temperature of the coldest month (MinTCM), temperature difference between the mean warmest and mean coldest month as a measure of continentality (TD), mean annual precipitation (MAP), mean precipitation growing season—November to March (PGS), summer climate moisture deficit (SCMD), annual climate moisture deficit (ACMD) based on Penman–Montieth method to estimate atmospheric evaporative demand (see Wang et al. 2012; Hamann et al. 2013 for more details) (Table 1). The climate variables MAP and MAT, and the variables related to moisture deficit were found to be important as drivers of productivity and G $\times$ E in radiata pine (Palmer et al. 2009; Kirschbaum and Watt 2011; Ivkovic et al. 2015). MinTCM and MAP were found to be main drivers of G $\times$ E in New Zealand (Gapare et al. 2015).

Statistical analysis

The climate variables MAP and MAT where uncorrelated ($r < 0.05$). MAP was highly correlated ($r > 0.93$) with PGS and ACMD, while MAT was highly correlated ($r > 0.85$) with MinTCM. Principal component analysis (PCA) was used for dimensionality reduction and pattern recognition classifications (Venables and Ripley 2002), implemented with the '*princomp*' function of the R v3.02 programming environment (R Development Core Team 2014). Climate correspondence of plantation regions to test sites was determined in two analyses: one for current and one for projected future climate. The similarity between current or future climate of plantation regions and current climate of test sites was determined by the shortest Mahalanobis distance between a plantation region climate to each test site climate. The Mahalanobis distance is the Euclidean distance of principal components, and therefore accounts for colinearity in climate data. The calculation was implemented with the '*distance*' function of the '*ecodist*' package for the R v3.02 programming environment (R Development Core Team 2014).

Results and discussion

The realized climate niche of radiata pine plantations

Commercial radiata pine plantations have been established across a wide range of environments in Australia and New Zealand with mean annual temperatures ranging from 9.0 to 16.4 °C and mean annual precipitation from 728 to 3359 mm in terms of regional averages (Fig. 2; Table 1). The climate where radiata pine is planted in Australia varies from Mediterranean, with distinctly dry and hot summers (e.g. Western Australia and Green Triangle), to temperate climates with no dry season and warm summers (e.g. Central Tablelands) or mild summers (e.g. Tasmania). In New Zealand climates vary from subtropical in the far north (e.g. Northland) to cool temperate climate in the far south (e.g. Otago-Southland). More detailed assessments, in Appendix Fig. S1.1 and S1.2, show strong seasonal differences with different timing and severity of moisture deficits. Notable

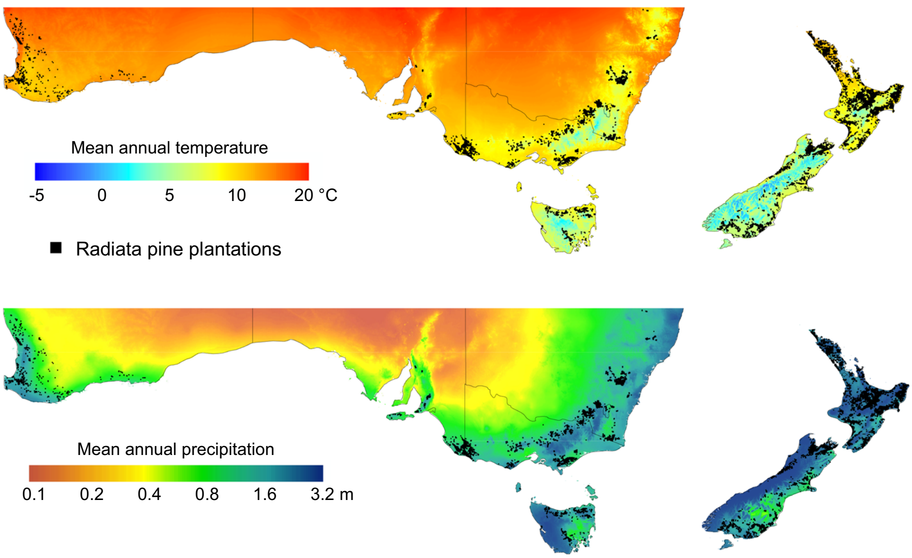

Fig. 2 Mean annual temperature (*top*) and mean annual precipitation (*bottom*) for regions where radiata pine has been planted. More climate variables for representative regions are shown in the Table 1. Note that the position of New Zealand (*right*) relative to southern Australia (*left*) is not drawn to scale

contrasting niches are, for example, Western Australia with a pronounced water deficit between November and March, and Northern Tablelands with pronounced summer rainfall. Wet summer periods were also widespread in New Zealand (e.g. West Coast, Bay of Plenty).

Observed and projected climate change

Observed climate trends in temperature and precipitation are visualized as the difference between the 1961–1990 climate normal and a recent 15-year average period from 1995 to 2009 (Fig. 3, left). The difference between these two periods represent an approximately 25-year climate trend (i.e. the time between the midpoints 1976 and 2002 of the two periods). Observed warming trends are restricted to the interior of Australia, while trends toward drier conditions are most pronounced in the east. In contrast, the average multi-model climate projections predict increased temperature and decreased rainfall for most of southern Australia (Fig. 3, middle). Exceptions are Northern and Central Tablelands in New South Wales, where an increase in rainfall is projected. Temperature predictions have a higher degree of confidence than rainfall predictions. Uncertainty is quite small in areas where radiata pine plantations are grown (Fig. 3, right).

The main uncertainty in temperature projections relates to how much CO_2 and other greenhouse gases will be emitted between now and the latter part of this century. Here, we use the RCP4.5 scenario, which represents a median CO_2 concentration forcing equivalent by the 2050s, implemented in the fifth phase of the Coupled Model Inter-comparison Project (CMIP5) (Meinshausen et al. 2011). The range of projections from these models in mean annual temperature (MAT) and mean annual precipitation (MAP) for radiata pine plantation regions in Australia and New Zealand are shown in Fig. 4. It is possible to use an average of all available models (dotted lines in Fig. 4), but this practice has generally been discouraged because it leads to climate variable combinations that may lack realism.

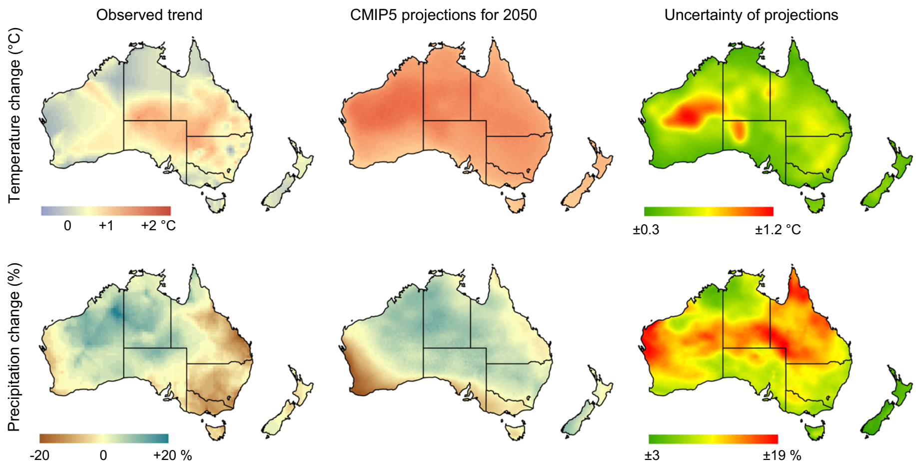

Fig. 3 Observed climate trends as difference between the 1961–1990 normal period and a recent 15-year average period from 1995 to 2009. Projections for 2050 are an average of the CMIP5 multi-model projections for the RCP 4.5 scenario corresponding to the IPCC Assessment Report 5 (IPCC 2013). Uncertainty in multi-model projections is expressed as ±1 standard deviation from the mean (i.e. approximately 68 % of the model projections fall within the color-coded uncertainty range)

Here, we choose one of the most advanced GCM implementations, HadGEM2–ES, one of the first GCMs that has included earth system components such as terrestrial and ocean carbon cycles. The model was also selected because it reflects an observed trend towards drier conditions in eastern and south-western Australia, likely an important factor for radiata pine forestry in these regions. For these reasons, the model has been selected in previous climate change studies of plantation forests of the region (e.g. Battaglia et al. 2009; Kirschbaum et al. 2012).

Current test sites and future regional climates

The plot of Principal Component (PC) climate variables in Fig. 5 (left plot) shows the long-term (1961–1990) average climate for plantation regions and the climate during test periods in Australia. The first two PC variables explained more than 85 % of the variation in the original climate variables. The higher vertical axis in the plot means warmer overall (i.e. increase in MAT) and in particular warmer winters (i.e. increase in minTCM) and more maritime climate, while the lower vertical axis represents a more continental climate (i.e. increase in annual temperature difference—TD). The higher direction on horizontal axis means overall wetter climate with cooler summers, while the lover direction on horizontal axis means warmer summers (i.e. increase in maxTWM) and drier overall.

The coverage of this climate space by radiata pine field tests was variable, with some regions in Australia not currently being covered at all (i.e. Bombala-East Gippsland) and some regions (i.e. Northern, Central and Southern Tablelands, Central Victoria, Mount Lofty and Kangaroo Island and Western Australia) only partially covered. The coverage of the climate space by tests was variable in New Zealand, with West Coast region not covered and some regions being poorly covered (i.e. Southern Northern Island) (Fig. 5; Table 2).

The plot of the first two PC variables in Fig. 5 (right plot) shows how the future climate of radiata pine plantation regions in Australia will shift relative to the climate during test periods. The test positions (triangles) in the PC coordinate system are fixed because they

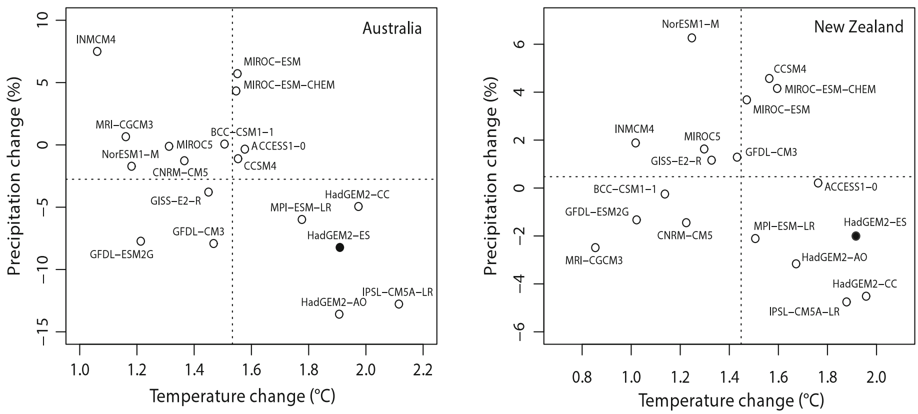

Fig. 4 Climate change projections (CMIP5, RCP 4.5, 2050) for radiata pine plantation regions in Australia (*left*) and New Zealand (*right*) using 1961–1990 normal period as reference. The scenario HadGEM2-ES chosen for this study is represented by *filled circles*, the *open circles* represent other models. The *dashed lines* represent means for 18 climate change models

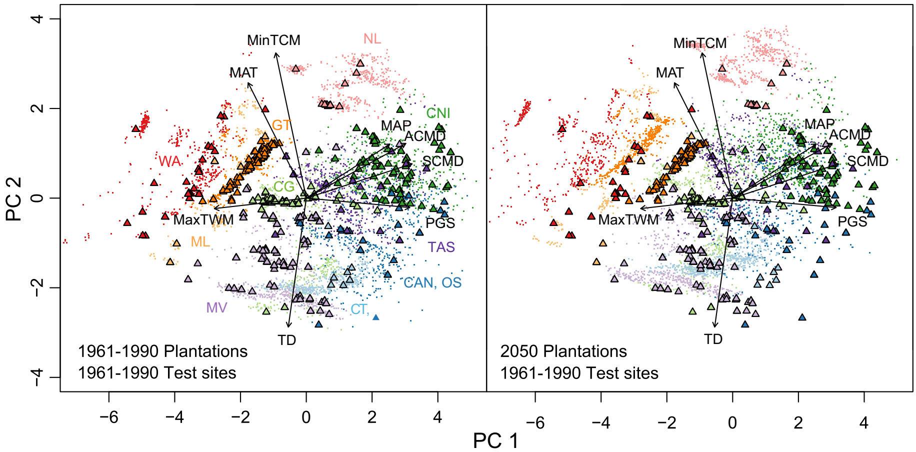

Fig. 5 Principal component based analysis of expected climate shifts of plantation regions relative to genetic test plantations according to HadGEM-ES projections for 2050. For example, the best genotypes for projected 2050 climate of the *Green Triangle* (GT) region may be selected based on Western Australia (WA) test sites. Climate variables included in the analysis are mean annual temperature (MAT), maximum temperature of the warmest month (MaxTWM), minimum temperature coldest Month (MinTCM), temperature difference (TD), precipitation November to March (PGS), summer climate moisture deficit (SCMD), annual climate moisture deficit (ACMD)

relate to historic time periods, while the plantation regions (dots) will experience a shift in the climate. The shifts according to HadGEM2–ES model 2050 were significant. The most significant shifts in Australia were of Tasmania's climate becoming more like that of current Central Gippsland, and the Green Triangle region moving towards warmer and drier space similar to the current climate of Western Australia. Northern, Central and Southern Tablelands and parts of the Western Australian region moved into a new currently unrepresented climate space.

For New Zealand, the most notable climate shifts are those of the Nelson/Marlborough plantation region becoming equivalent to the climate space currently occupied by the Southern North Island and East Coast plantations. The climate of West Coast and parts of Otago-Southland region will become more like the current Central North Island climate. For the warm, northern regions, few of the existing test sites will provide an appropriate representation of projected future climate conditions. By the 2050s, the plantation regions in the Central North Island, Hawke's Bay, Southern North Island, West Coast, and Canterbury essentially lack equivalent test sites under reference climate conditions (Fig. 5 right; Table 2).

Recommendations and limitations

A more detailed quantitative analysis of the principal component ordination shown in Fig. 5 is given in Table 2. By the 2050s, future climates of most important plantation regions are projected to match climates currently present in different regions, and the number of test sites that are representative of climate in a certain region will change. Table 2 lists plantation areas for each region, which conveys their relative importance. It also gives the number of test sites that have information useful for making genetic

Table 2 Quantitative analysis of the principal component ordination shown in Fig. 5

Region (abbreviation)	Plantation area (ha)	Number of tests	Matching tests 2050	Matching region 2050
Australia				
Western Australia (WA)	56,400	34	3	WA
Mount Lofty ranges and Kangaroo Island (ML)	19,400	6	8	WA
Green Triangle (GT)	176,300	87	28	WA
Northern Tablelands (NT)	16,300	5	0	
Central Tablelands (CT)	81,200	2	55	MV
Southern Tablelands (ST)	22,000	2	0	
Murray Valley (MV)	185,600	86	31	MV
Central Victoria (CV)	31,000	21	0	
Central Gippsland (CG)	62,000	49	100	GT, CG
East Gippsland-Bombala (EGB)	46,200	0	15	MV, CV, CG
Tasmania (TAS)	74,900	14	42	CG
New Zealand				
Northland/Auckland (NL)	195,700	13	13	NL
Central North Island (CNI)	521,700	33	0	
East Coast (EC)	151,400	29	13	CNI
Hawke's Bay (HB)	128,800	4	0	
Southern North Island (SNI)	160,000	3	0	
Nelson/Marlborough (NM)	157,300	6	50	CNI, EC
West Coast (WC)	23,000	0	0	
Canterbury (CAN)	85,700	4	0	
Otago/Southland (OS)	130,500	12	53	EC, MV, OS

The plantation area is shown to convey the importance of plantation regions. The number of test sites represent information available to make genetic selections appropriate for the plantation regions at present. Matching tests 2050 refers to the number of test sites that may be used for selecting genotypes under climate change predicted by the selected HadGEM-ES model for 2050. Matching region 2050 is the climate region that is the closest current equivalent to the projected 2050 climate environment

selections appropriate for the plantation regions at present and under projected future climate, and the best matching current test site climate for plantation region climate projected to 2050s.

The analysis reveals that making appropriate genetic selections under future climates will be less problematic in some regions then in others. For example, the future planting conditions of the Central Tablelands in New South Wales will be very well covered by a large number of trials in the Murray Valley region. In fact, the coverage with climatically matching trials will be better than today. The five most important planting regions in Australia, MV, GT, CT, TAS, CG have good test site coverage maintained. With the exception of Western Australia, only minor planting regions are expected to be poorly covered by appropriate test sites (Table 2).

In New Zealand, one might expect the subtropical Northland (NL) test sites to be a good match for other North Island planting regions (e.g. CNI, EC, HB, SNI) in the future.

However, projected climate change is not large enough in magnitude by the 2050s for this to happen (which can be seen in Fig. 5). Yet, we would expect those test sites to eventually match future climates of these planting regions, especially the Central North Island (CNI), which is by far the most important planting region in New Zealand. In turn, the majority of current test sites located in on New Zealand's North Island are predicted to be most useful for genotype selection for important planting regions of the New Zealand's South Island (NM, OS). A notable match was also the Murray Valley (MV) trials for Otago Southland (OS) planting region future climates, the only match across Australia and New Zealand observed in this study.

Prevalent gaps in trail coverage projected for the future may be caused by gaps in trial coverage at present. The regions WC, CAN, HB, NT and ST are examples (Table 2). This issue could be addressed by establishing tests at the warmer, low elevation or northern end of climate envelopes of these regions. It should be noted, however, that these planting regions are secondary in importance within Australia and New Zealand. Climate shifts toward no-analogue conditions are most likely for the regions Western Australia (WA) and Northland (NL) in New Zealand. There are limited options to address this issue, except perhaps to include in the analyses other regions of the world where radiata pine is grown, such as Chile, South Africa and/or Spain to find analogues to future climates that are not covered by test sites in this analysis. Alternatively, process based models (e.g. Battaglia et al. 2009; Kirschbaum and Watt 2011) could be calibrated for specific genotypes and used to predict their performance in the future for the regions that lack trials with equivalent climate.

It should be noted that this study, evaluating the climate match between test sites for genetic selection and planting regions for selected planting stock, does not imply that a mismatch would automatically lead to reduced productivity under status-quo management. Climate change may actually lead to an overall productivity increase without any intervention (e.g. Battaglia et al. 2009; Pinkard and Bruce 2011; Kirschbaum and Watt 2011; Pinkard et al. 2014). Nevertheless, appropriate planting stock selection based on matching test site information might further increase productivity under generally more benign growing conditions.

We should also note that this paper does not address the role of other factors influencing growth and survival, such as soil type, site quality, or silvicultural treatments and their interaction with climate. A comprehensive climate change adaptation strategy for radiata pine plantations in New Zealand and Australia could pursue additional management interventions. Examples may include changes in site selection where radiata pine appears to be limited by climatic factors, e.g. planting on more mesic sites where summer dry periods become problematic. Nevertheless, with climate shown to be an important driver of genotype by environment interactions (e.g., Ivković et al. 2015; Gapare et al. 2015), selection of improved planting stock from trial sites that actually match a changed plantation region climate will be essential to maintain and improve the productivity of Australia's and New Zealand's radiata pine plantations.

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Appendix 1. Plantation regions and Walter & Lieth climate diagrams of radiata pine plantations in Australia and New Zealand.

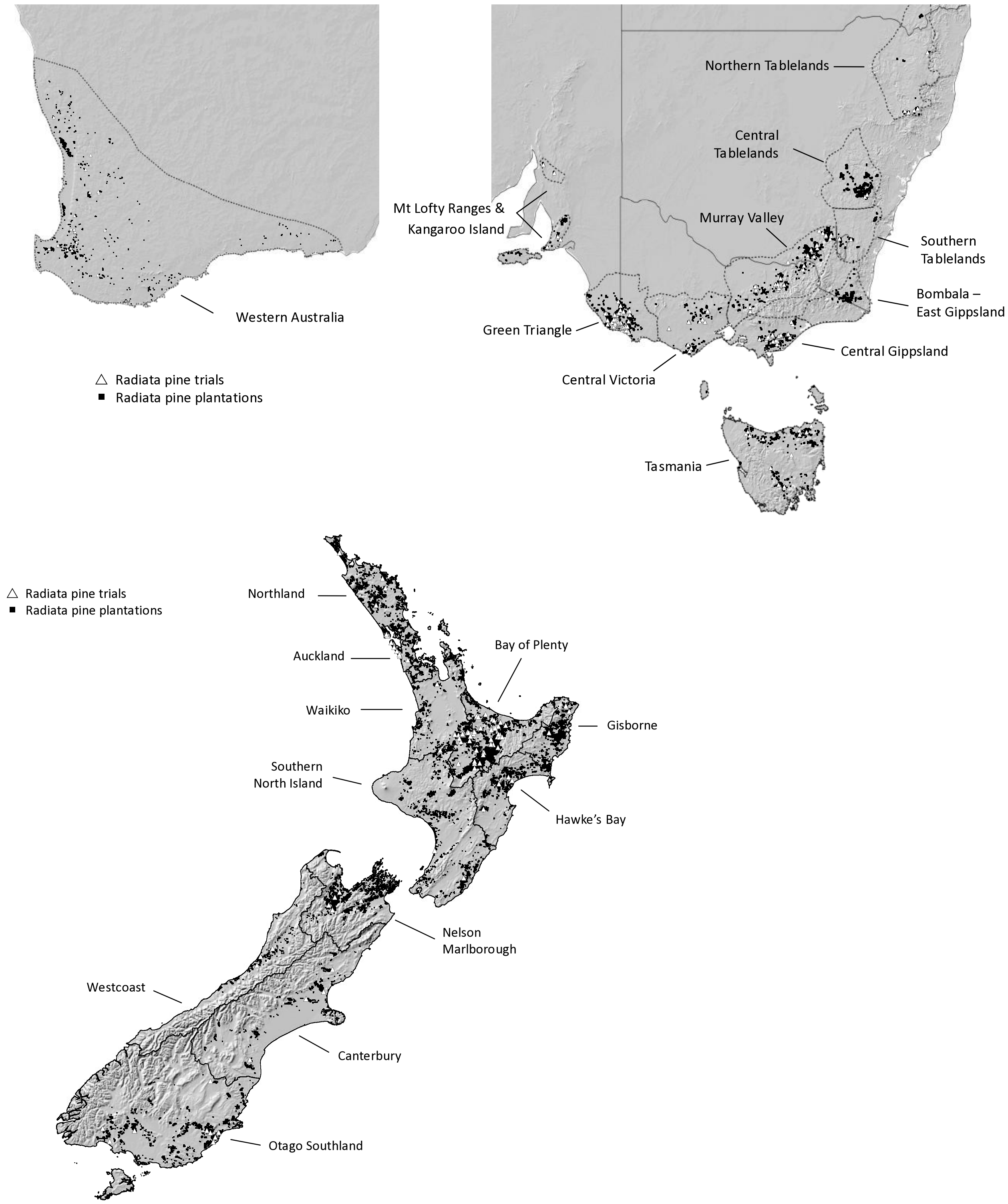

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Fig S1.1. Plantation regions for Australia and New Zealand.

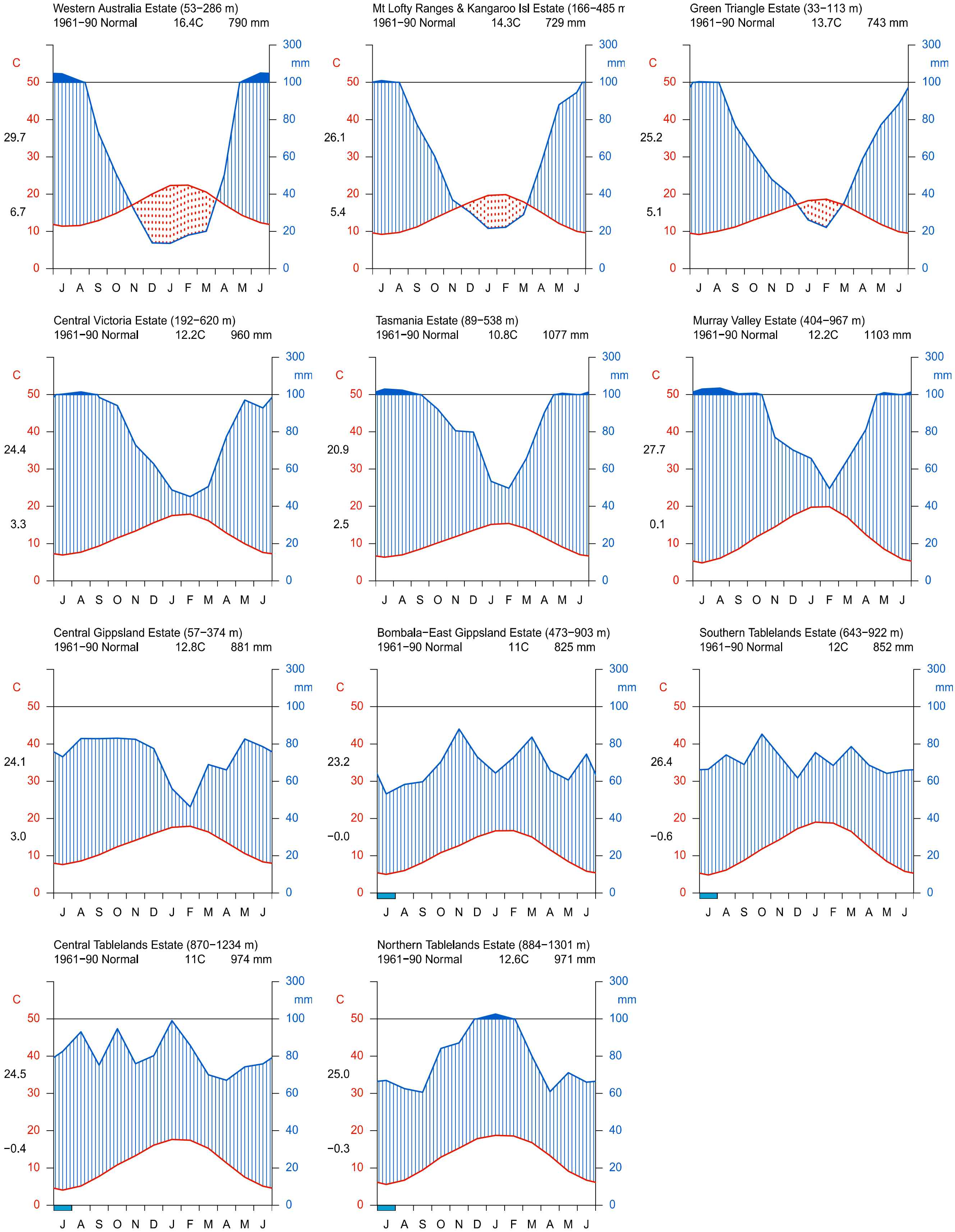

Fig S1.2. Walter & Lieth climate diagrams of radiata pine plantations in Australia. The plots report region and the 10th to 90th percentile of the elevation range of plantations in the title. Below the title, mean annual temperature (MAT) and mean annual precipitation (MAP) are reported. Mean maximum temperature of the warmest month (MaxTWM) and mean minimum temperature of the coldest month (MinTCM) are shown next to the y-axis.

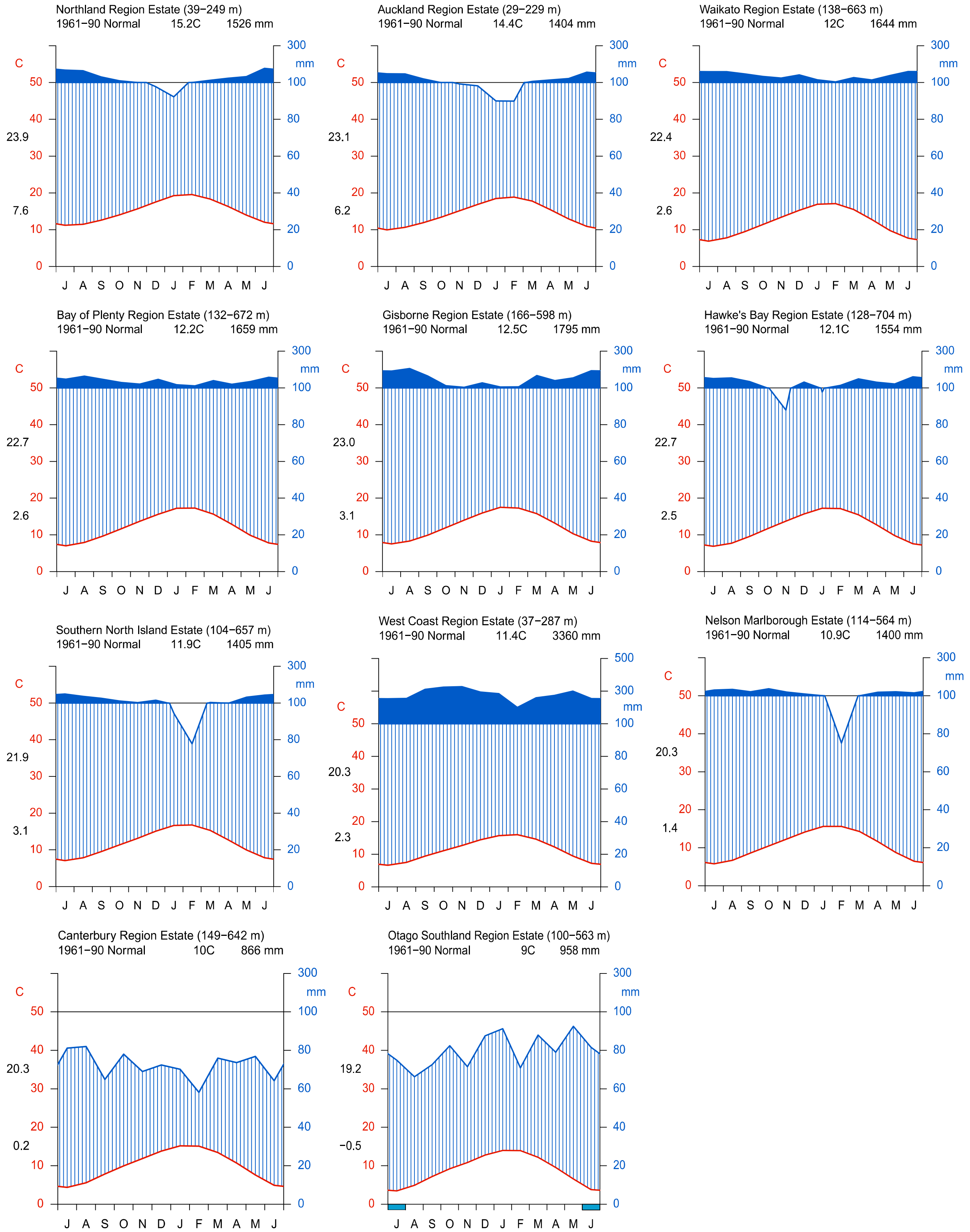

Fig S1.3. Walter & Lieth climate diagrams of radiata pine plantations in New Zealand. The plots report region and the 10^{th} to 90^{th} percentile of the elevation range of plantations in the title. Below the title, mean annual temperature (MAT) and mean annual precipitation (MAP) are reported. Mean maximum temperature of the warmest month (MaxTWM) and mean minimum temperature of the coldest month (MinTCM) are shown next to the y-axis.