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RESEARCH ARTICLE

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Climate change impacts on agriculture's southern frontier – Perspectives for farming in North Patagonia

Ricardo del Barrio[1,2] | **Eduardo Fernandez**[3] | **Andrea S. Brendel**[2,4] | **Cory Whitney**[3] | **José A. Campoy**[5] | **Eike Luedeling**[3]

[1]Escuela de Producción, Tecnología y Medio Ambiente, Sede Atlántica, Universidad Nacional de Río Negro, Viedma, Argentina

[2]Departamento de Agronomía, Universidad Nacional del Sur (UNS), Bahía Blanca, Argentina

[3]Institute of Crop Science and Resource Conservation (INRES) – Horticultural Sciences, University of Bonn, Auf dem Hügel 6, Bonn, 53121, Germany

[4]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Instituto Argentino de Oceanografía (IADO), Universidad Nacional del Sur (UNS)-CONICET, Bahía Blanca, Argentina

[5]Department of Chromosome Biology, Max Planck Institute for Plant Breeding Research, Cologne, Germany

Correspondence
Eduardo Fernandez, Institute of Crop Science and Resource Conservation (INRES) – Horticultural Sciences, University of Bonn, Auf dem Hügel 6, Bonn 53121, Germany.
Email: efernand@uni-bonn.de
José A. Campoy, Department of Chromosome Biology, Max Planck Institute for Plant Breeding Research, Carl-von-Linne-Weg 10, Cologne 50829, Germany.
Email: campoy@mpipz.mpg.de

Abstract

Winter chill is expected to decrease in many of the suitable growing regions for deciduous trees. Argentinean North Patagonia hosts extensive fruit tree cultivation, which provides an important contribution to both local and global food security. Using historic records from 11 weather stations from North Patagonia, we evaluate the possible impacts of climate change on fruit tree cultivation. We assess winter chill and seasonal heat availability, and the risk of spring frost events based on outputs from 15 Global Climate Models (GCMs) for two Representative Concentration Pathway (RCP) scenarios and two future time periods (represented by central years 2050 and 2085). Metrics were estimated for 47 years of records from the weather stations, as well as typical conditions for 10 past scenarios and 60 future GCM and RCP projections. Scenarios consisted of 100 plausible annual temperature records produced by a weather generator. Results suggest that fruit tree dormancy in Argentinean North Patagonia will not be strongly affected by climate change. Compared to the past, winter chill may only decrease by 9% in the RCP4.5 scenario by 2050 in the northeastern and eastern subregion, while in the central-south and west the reduction seems unlikely to exceed 6% by the same RCP scenario and year. Our models project stable high growing season heat in the northeastern and eastern regions, and major increases in the south by 2085 in both RCP scenarios. Projections of spring frost events varied between 0 and about 25 hours below 0°C depending on the site. Increasing heat availability may create opportunities for fruit and nut growers to introduce new species and cultivars to the region. Our results provide a basis for planning such introductions and for enabling growers to exploit new opportunities for producing temperate orchard crops beyond their traditional ranges.

KEYWORDS

chill models, chill requirement, heat requirement, *Prunus* sp., spring frost risk, temperate trees, warm winters

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1 | INTRODUCTION

Optimal agricultural productivity depends on an adequate match between plant phenology and environmental conditions (Forrest and Miller-Rushing, 2010; Polgar and Primack, 2011). The growing season for deciduous trees starts with bud burst and leaf unfolding in spring and continues until leaf fall in the following autumn (Faust *et al.*, 1997; Considine and Considine, 2016). In late autumn and winter, trees undergo a stage of dormancy to survive unfavourable thermal conditions (Campoy *et al.*, 2011b; Fadón *et al.*, 2020). Scientific evidence suggests that dormancy-related processes are driven mainly by thermal and photoperiodic fluctuations (Singh *et al.*, 2018; Tylewicz *et al.*, 2018; Singh *et al.*, 2019). In deciduous fruit and nut trees, temperature is usually considered the principal driver of dormancy and subsequent bud burst (Egea *et al.*, 2003; Alburquerque *et al.*, 2008; Cooke *et al.*, 2012; Laube *et al.*, 2014; Guo *et al.*, 2015b; Benmoussa *et al.*, 2017). Similarly, growth after bud burst seems to be mainly modulated by temperature (Kramer *et al.*, 2017). Inadequate temperature conditions during the dormancy period, for example extremely warm temperatures during winter or freezing temperatures during the growing season, may affect growth and therefore tree yield, which in turn can compromise the economic viability of deciduous fruit orchards.

During the dormancy stage, deciduous trees require a certain exposure to cold temperatures (referred to as their “chill requirement”; CR), after which they can start accumulating heat until reaching budburst (Campoy *et al.*, 2012). The need for warm temperatures is expressed by the concept of heat requirement (Couvillon and Erez, 1985; Kramer *et al.*, 2017). The relationship between heat and chill requirements is not fully understood, but it seems likely that additional heat may help trees partly compensate for lack of chill (Harrington *et al.*, 2010; Campoy *et al.*, 2011a; Pope *et al.*, 2014). Related to this, a residual effect of dormancy has been described as a reduction of heat requirements with increased chilling (Spiegel-Roy and Alston, 1979; Couvillon and Erez, 1985; Okie and Blackburn, 2011; Laube *et al.*, 2014).

Several models have been proposed for estimating chill requirements in deciduous fruit trees. Among these models, the most commonly used are the Chilling Hours model (Bennett, 1949; Weinberger, 1950), the Utah model (Richardson *et al.*, 1974), the Positive Utah model (Linsley-Noakes *et al.*, 1994) and the Dynamic Model (Fishman *et al.*, 1987a; 1987b; Erez *et al.*, 1990). Results of several comparisons between these models have identified the Dynamic Model as the most reliable chill model developed so far (Luedeling and Brown, 2011; Zhang and Taylor, 2011; Darbyshire *et al.*, 2013).

However, chill models alone cannot explain the occurrence and timing of phenological stages such as date of bud burst or bloom. For explaining – or even predicting – such dates, chill models need to be combined with forcing (heat) models (Luedeling, 2012). Heat has been commonly computed using the Growing Degree Hours (GDH) model (Anderson *et al.*, 1986). Recent modelling approaches to explain flowering dates of deciduous fruit trees have included chill and heat accumulation as related processes (Maulion *et al.*, 2014; Darbyshire *et al.*, 2017). Such an approach seems biologically plausible and might improve the accuracy of chill models in predicting bloom dates (Chuine *et al.*, 1998; Chmielewski *et al.*, 2011; Chuine *et al.*, 2016). Accurate models can play a fundamental role in selecting tree species and cultivars for specific locations. For the achievement of commercially successful fruit production in temperate and cold-temperate climates, cultivars must be able to fulfil their winter chill requirements and flower in a period with low risk of spring frost (Okie and Blackburn, 2011).

Tree phenology depends largely on temperature, making it sensitive to global warming (Menzel *et al.*, 2006; Augspurger, 2013). Studies suggest that the beginning of the growing season of woody plants has advanced by 2.3 days per decade during recent decades in temperate Europe (Parmesan and Yohe, 2003; Root *et al.*, 2003). Global temperatures have risen by 0.8°C over the past 100 years, and they are widely expected to increase substantially throughout the 21st century (Alexander *et al.*, 2006; Brown *et al.*, 2008; Buckley and Huey, 2016). These changes are expected to have severe environmental, biological and socio-economic implications (IPCC, 2014). A number of studies predict climate change impacts including greater incidence of pests (Garrett *et al.*, 2006; Gregory *et al.*, 2009; Luedeling *et al.*, 2011b), phenological shifts (Badeck *et al.*, 2004; Pope *et al.*, 2013; Funes *et al.*, 2016), spring frost events (Kunz and Blanke, 2016; Campos *et al.*, 2017) and winter chill availability (Baldocchi and Wong, 2008; Luedeling *et al.*, 2011a; Guo *et al.*, 2013; Luedeling *et al.*, 2015; Fernandez *et al.*, 2020). These changes will be a challenge for growers in many major fruit production regions around the world.

For exploring future conditions, the Intergovernmental Panel on Climate Change (IPCC) recommends considering four Representative Concentration Pathways (RCPs) of atmospheric greenhouse gas concentrations (IPCC, 2014). These include a strict mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high atmospheric greenhouse gas concentrations (RCP8.5). All of these scenarios are expected to affect thermal conditions in most temperate tree fruit production areas of the world (Luedeling, 2012).

For deciduous orchards to remain productive in a changing climate, future availability of both winter chill and growing season heat must be assured, as well as an acceptable risk of exposure to late spring frost (Guo *et al*., 2019). Forecasts of both regional and local climate change impacts are needed to help anticipate changes in these important factors and to adjust agricultural management accordingly. These changes may depend strongly on the region of interest (Luedeling *et al*., 2011a),.

Most of the production orchards of deciduous fruits in Argentina are located in Patagonia, the southernmost region in the country, where 85% of Argentina's apples and 75% of its pears are produced (CAFI, 2019). The productive orchards in the irrigated valleys of the North-Patagonian subregion make Argentina the largest exporter of pears in the Southern Hemisphere and the fifth in apples worldwide (CAFI, 2019). Future climate change may affect the agroclimatic potential of these orchards, compromising production in some regions and opening new opportunities in those parts of the country that are currently too harsh. Temperature increases of up to 1°C have already occurred between 1960 and 2010 (SAyDS, 2015), and seasonal changes in surface temperature by up to 3°C in summer are expected by the end of the 21st century (Cabré *et al*., 2016). Studies on the likely effects of climate change on agroclimatic conditions in North Patagonian could help to elucidate the prospects of fruit production in the region.

The main aim of this work was to evaluate historical trends and predict future changes in winter chill, growing season heat and the risk of late spring frost, which are prominent factors defining the cultivation potential of deciduous fruit trees. We evaluated past weather scenarios and future projections for 11 sites across the North Patagonian region for two RCP scenarios (RCP4.5 and RCP8.5) using 15 climate models.

2 | MATERIALS AND METHODS

We used the R programming language (R Core Team, 2019) for all analyses.

2.1 | Study area and meteorological data

The study area comprised the North Patagonia region of Argentina, which is located between 39°S and 44°S. This area includes the south of Buenos Aires Province and the entire provinces of Río Negro, Neuquén and Chubut. We selected 11 sites across this region according to their current and expected future agroclimatic suitability for deciduous fruit tree production. These sites were Neuquén and Río Colorado in the north, Hilario Ascasubi, Viedma, Trelew and Comodoro Rivadavia in the east (northeast to southeast), Maquinchao and Paso de Indios in the central south, and Bariloche, El Bolsón and Esquel in the west (Figure 1).

Meteorological data were obtained from weather stations at each site (Table 1), which belonged either to the National Weather Service (SMN, https://www.smn.gob.ar) or to the National Institute of Agricultural Technology (INTA, https://www.argentina.gob.ar/inta). Daily minimum and maximum temperatures for the period between 1971 and 2017 were downloaded for all sites.

Since many records were not complete (Table 1), we filled data gaps following the procedure described in Fernandez *et al*. (2020) by using functions of the "chillR" package (Luedeling, 2019). In brief, we listed the 24 closest weather stations to be used as secondary sources of data. Using the listed stations, we downloaded minimum and maximum daily temperatures from stations located less than 350 km away from the primary source of data and covering more than 10 years of the period of interest. We filled the gaps by taking data from the listed weather stations, after correcting for any between-station biases that we found. To avoid including nonrepresentative data we used a maximum bias between primary and secondary stations of 5°C. Remaining gaps were filled by linear interpolation according to the procedure described by Luedeling (2018).

2.2 | Climatic clustering

We grouped the weather stations into subregions by means of cluster analysis to summarize the large amount of available information for the 11 stations, three metrics, two RCP scenarios, two future years and 15 climate models. This helped us to select a set of representative stations that covered the intra-regional variability of climatic conditions. The Argentine North Patagonia region has two significant climatic gradients: (a) a temperature gradient, with temperatures decreasing from northeast to southwest and (b) a rainfall gradient, with precipitation decreasing from west to east (Coronato and Bisigato, 1998; Alessandro, 2008). The region also has high altitudinal variability. We applied Ward's cluster analysis (Ward, 1963) using rescaled Euclidean distance as a dissimilarity measure to group meteorological stations based on the thermal and topographic metrics considered in this study (Table 1), as well as the annual and cold-

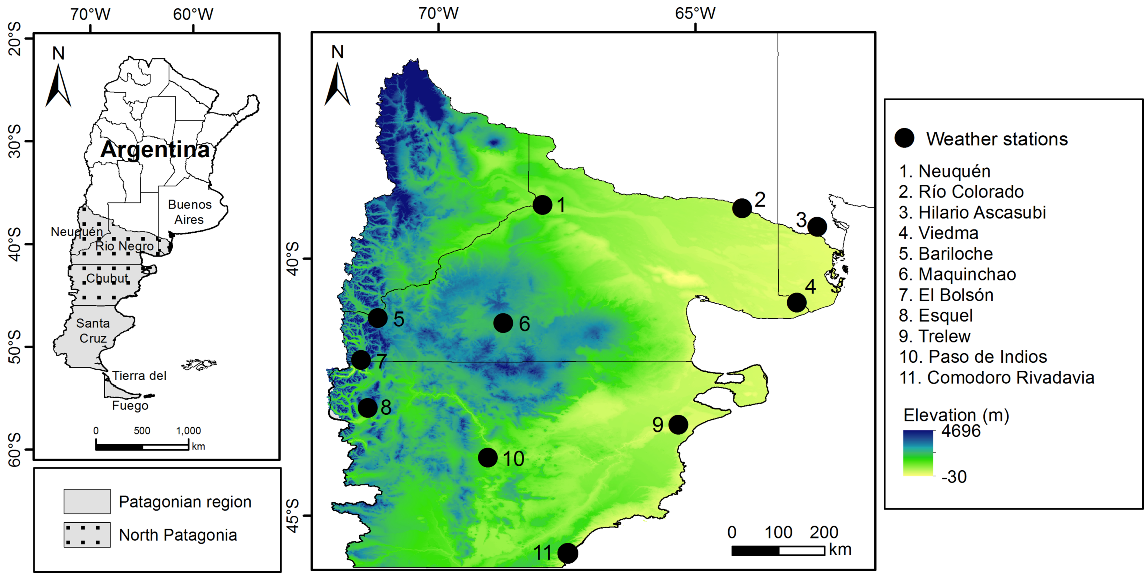

FIGURE 1 Location of the weather stations used as primary sources for the analysis of past and future agroclimatic conditions for deciduous tree fruit production in North Patagonia, Argentina

TABLE 1 Data on 11 weather stations in North Patagonia, Argentina used as primary sources of temperature data. Means and completeness information refer to the period 1971–2017

	Geographic coordinates		Elevation	Temperature (°C)			Completeness
Weather station name and map location[a]	**Lat.**	**Long.**	**m above mean sea level**	**Annual mean**	**Mean daily maximum in January**	**Mean daily minimum in July**	**% records available**
Neuquén (1)	38.95°S	67.97°W	271	14.8	31.7	0.3	99.55
Río Colorado (2)	39.02°S	64.08°W	59	15.9	31.7	2.7	83.65
Hilario Ascasubi (3)	39.38°S	62.62°W	22	14.9	30.0	1.6	96.42
Viedma (4)	40.85°S	63.02°W	7	14.4	29.3	1.6	97.47
Bariloche (5)	41.15°S	71.17°W	840	8.3	22.4	−1.5	99.40
Maquinchao (6)	41.25°S	68.73°W	887	10.2	26.3	−4.0	96.71
El Bolsón (7)	41.97°S	71.50°W	337	10.1	24.7	−0.8	75.49
Esquel (8)	42.90°S	71.37°W	787	8.6	18.9	−2.6	91.17
Trelew (9)	43.23°S	65.32°W	10	13.9	28.9	0.6	98.26
Paso de Indios (10)	43.87°S	69.03°W	590	10.7	26.5	−2.3	86.79
Comodoro Rivadavia (11)	45.75°S	67.45°W	46	13.2	25.9	2.7	99.59

[a] Numbers in parentheses represent the numbering in the central panel of Figure 1.

semester mean rainfall. This clustering method is well suited for the study of thermo-pluviometric variability (Lu *et al.*, 2017; Ferrelli *et al.*, 2019). We selected a cut-off point to define the optimal number of clusters according to the "elbow" method. Cluster analysis revealed three homogeneous subregions (clusters with similar meteorological and topographic conditions) among the 11 primary stations.

2.3 | Analysis of historic trends

Results emerging from historic climate trend analyses are sometimes difficult to interpret due to interannual variation, which obscures long-term trends. This can make climate-related agricultural planning and management risks difficult to estimate. Yet management decisions often depend on the ability to quantify such risks. To overcome this difficulty and allow for risk evaluation, we used the RMAWGEN weather generator (Cordano and Eccel, 2016), which is accessed by the "chillR" package (Luedeling, 2019), to produce representative scenarios of past weather. Each of these scenarios consisted of 100 replicates of plausible meteorological data for each year of interest given the local climate at the respective time. The weather generator was trained with all available data to produce scenarios for 11 years across the historic record. We used a running mean function over 15 years to compute the typical daily mean and maximum temperatures for each month of each year and used these data to train the weather generator. We then used the weather generator to generate 100 replicates of plausible temperature data for each scenario year.

We probed the historic datasets for past trends in selected metrics, using the nonparametric Mann-Kendall test (Mann, 1945; Stuart, 1956) to calculate trends and Sen's slope estimator (Sen, 1968) to quantify rates of change, using the "trend" package (Pohlert, 2018).

2.4 | Projected future scenarios

To evaluate possible future agroclimatic conditions for all sites, we obtained future climate projections from the Climate Wizard database and programming interface (https://github.com/CIAT-DAPA/climate_wizard_api) maintained by the International Center for Tropical Agriculture (CIAT). This was used together with functions contained in the "chillR" package (Luedeling, 2019). The Climate Wizard database contains projections for 15 Global Climate Models (Table 2) for two Representative Concentration Pathways (RCP4.5 and RCP8.5). These scenarios represent a total radiative forcing of 4.5 $W\cdot m^{-2}$ and 8.5 $W\cdot m^{-2}$ by the end of the 21st century (IPCC, 2014). In both RCP scenarios, temperature projections were obtained for the period 2035–2065, and for the period 2070–2100. These time intervals were represented by their central years 2050 and 2085, respectively. We used these scenarios to feed the weather generator and obtain data for 100 simulated years for each combination of site, RCP, year and climate model.

TABLE 2 Global climate models used for future temperature projections in North Patagonia, Argentina

Organization	Model version	Abbreviation	Reference and/or link
Beijing Climate Center	Climate System Model 1.1	bcc-csm1-1	http://forecast.bcccsm.ncc-cma.net/web/channel-43.htm Wu (2012)
Geophysical Fluid Dynamics Laboratory	Earth System Model 2G	GFDL-ESM2G	https://www.gfdl.noaa.gov/earth-system-model/ Delworth et al. (2006)
	Earth System Models 2M	GFDL-ESM2M	
	Climate Model 3	GFDL-CM3	Donner et al. (2011)
Institute of Numerical Mathematics	Climate Model Version 4	inmcm4	Volodin et al. (2010)
Institute Pierre – Simon Laplace	Climate Model 5A Low Resolution	IPSL-CM5A-LR	https://cmc.ipsl.fr/ipsl-climate-models/ipsl-cm5/
	Climate Model 5A Mid Resolution	IPSL-CM5A-MR	
Community Climate System Model	Version 4	CCSM4	http://www.cesm.ucar.edu/models/ccsm4.0/
Community Earth System Model	Version 1 – BioGeoChemical model enabled	CESM1-BGC	Lindsay et al. (2014)
Beijing Normal University	Earth System Model	BNU-ESM	Ji et al. (2014)
Canadian Earth System Model	Version 2	CanESM2	Chylek et al. (2011)
Model for Interdisciplinary Research On Climate	Earth System Model	MIROC-ESM	Watanabe et al. (2011)
Centre National de Recherches Météorologiques	Climate Model 5	CNRM-CM5	http://www.umr-cnrm.fr/spip.php?article126&lang=en
Australian Community Climate and Earth	System Simulator 1.0	ACCESS1-0	Bi et al. (2013)
Commonwealth Scientific and Industrial Research Organisation	Mark3.6.0	CSIRO-Mk3-6-0	Rotstayn et al. (2009)

2.5 | Climate-related metrics

Ten metrics were calculated for the historic record, for the plausible past scenarios and for the future weather scenarios at each site (Table 3). Here we report on winter chill, safe winter chill, growing season heat and the risk of spring frost. We expect that these metrics will be of central relevance for present and future decisions regarding the planning and management of temperate trees and orchards in Patagonia. Results for the remaining metrics are attached as Data S1.

Winter chill availability was estimated in Chill Portions (CP) according to the Dynamic Model (Fishman *et al.*, 1987a; Fishman *et al.*, 1987b; Erez *et al.*, 1990). We also computed Safe Winter Chill (SWC) for each station to account for adequate chill exposure in most years, rather than an average or median year. SWC is defined as the first decile of the winter chill distribution, representing the chill level expected to be exceeded with 90% probability in a given year (Luedeling *et al.*, 2009c).

We calculated growing season heat as an approximation of the thermal energy available for crop development, by using a modification of the Growing Degree Hours (GDH) Model (Anderson *et al.*, 1986). This modification considered 10 and 5°C ($\mathrm{GsGDH}_{10^\circ\mathrm{C}}$, $\mathrm{GsGDH}_{5^\circ\mathrm{C}}$) as base temperatures instead of the original value of 4°C for fruit trees. The Growing Degree Hours concept includes the "thermal time" concept, allowing for the evaluation of growing season restrictions due to unfavourable conditions, a consideration that can be critical in cold regions such as Patagonia. Finally, the occurrence of spring frosts was calculated by counting the hours with temperatures below 0°C ($\mathrm{SF}_{h<0^\circ\mathrm{C}}$) from October 1st to November 30th for each year.

3 | RESULTS

3.1 | Representative stations grouped by cluster analysis

The hierarchical association tree (dendrogram) produced by cluster analysis provided a framework of climatic similarity for all stations (Figure 2), showing a clear subregionalization: coastal areas in the north and east (Neuquén, Río Colorado, Hilario Ascasubi, Viedma, Trelew and Comodoro Rivadavia stations), the central south (Maquinchao and Paso de Indios stations) and the western Andean area (Bariloche, El Bolsón and Esquel stations). For further analyses, we selected Viedma and Trelew to represent the first cluster, Maquinchao for the second and Bariloche for the third. For these stations, we

TABLE 3 Climatic and agroclimatic metrics analysed for past and future weather scenarios in North Patagonia

Metric	Abbreviation	Definition	Unit
Winter chill accumulation	WCA	Winter chill availability between 1st April and 31st July	Chill Portions
Safe winter chill	SWC	First decile of winter chill distribution	Chill Portions
Early/autumn frost	$\mathrm{AF}_{h<0^\circ\mathrm{C}}$	Temperatures below 0°C between 1st April and 31st May	Hours
Late/spring frost	$\mathrm{SF}_{h<0^\circ\mathrm{C}}$	Temperatures below 0°C between 1st October and 30th November	Hours
Severe winter frost	$\mathrm{WF}_{h<-10^\circ\mathrm{C}}$	Temperatures below −10°C between 1st June and 31st August)	Hours
Early spring heat	$\mathrm{EsGDH}_{5^\circ\mathrm{C}}$	Accumulated number of growing degree hours (above 5°C) between 1st August and 31st October	Growing Degree Hours
Early spring heat	$\mathrm{EsGDH}_{10^\circ\mathrm{C}}$	Accumulated number of growing degree hours (above 10°C) between 1st August and 31st October	Growing Degree Hours
Growing season heat	$\mathrm{GsGDH}_{5^\circ\mathrm{C}}$	Accumulated number of growing degree hours (above 5°C) between 1st August and 31st March	Growing Degree Hours
Growing season heat	$\mathrm{GsGDH}_{10^\circ\mathrm{C}}$	Accumulated number of growing degree hours (above 10°C) between 1st August and 31st March	Growing Degree Hours
Extreme summer events	$\mathrm{ESu}_{h>38^\circ\mathrm{C}}$	Temperatures above 38°C between 1st December and 28th February	Hours

present detailed results here, whereas information of the remaining stations is included as Data S1.

3.2 | Historical and prospective future winter chill

Winter chill availability was assessed for past scenarios for all stations (Figure 3, left panel). Representative past weather scenarios produced by the weather generator show that historic chill ranged between 58 CP (5% quantile) and 75 CP (95% quantile) in Viedma and Trelew (representative of the red cluster in Figure 2). In Viedma the median chill availability was 68 CP in 1971 and 64 CP in 2017, while in Trelew estimated median chill was 68.5 CP in 1971 and 65.5 CP in 2017.

Both the western Andean and the central-south plateau areas showed higher historic chill levels than Viedma and Trelew. Specifically, Bariloche (representative of the blue cluster in Figure 2) showed historic median values of 83.5 CP (76 CP 5% quantile and 87 CP 95% quantile), and Maquinchao (representative of the green cluster in Figure 2) reported historic median values of 76.5 (68 CP 5% quantile and 83.5 CP 95% quantile), without major trends between 1971 and 2017.

Regarding future scenarios, results show average decreases in chill availability in the northeast and eastern subregion by 7.4% in the RCP4.5 scenario (−8.6% by 2050; −6.2% by 2085) and by 13.5% in the RCP8.5 scenario (−11.1% by 2050; −15.9% by 2085). In the central-south and west the decrease in available chill seems unlikely to exceed 6%, even in the most severe warming scenario (RCP8.5 by 2085; Figure 3).

Results from different climate models varied across regions, RCP scenarios and years. By 2050, results for the RCP4.5 scenario showed a slightly greater variation in estimations for the northern and eastern stations (Viedma and Trelew) compared to the western Andean and central-south plateau areas (Maquinchao and Bariloche). Such differences become more evident when comparing sites for the RCP8.5 scenario by the same year. Overall, most model projections show remarkable similarities. This consistency implies that despite some uncertainty about future conditions, fairly confident chill predictions are possible (Figure 3).

Historically observed Safe Winter Chill (SWC) ranged from 60.3 CP in Viedma and 59.8 CP in Trelew to 70.1 CP in Maquinchao and 78.8 CP in Bariloche. Concerning future prospects, SWC is expected to decrease by 20% in Viedma and 15% in Trelew by 2085 in the RCP8.5 scenario. In Maquinchao and Bariloche, decreases by between 7 and 8% are expected by the same RCP scenario and year (Figure 4).

3.3 | Historical and prospective future heat accumulation

Heat accumulation showed strong intra-regional variation, following regional thermal gradients, as expressed by the number of Growing Degree Hours above a base temperature of 10°C during the growing season ($\text{GsGDH}_{10^\circ\text{C}}$). Regarding past scenarios, growing season heat ($\text{GsGDH}_{10^\circ\text{C}}$) between 1st August and 31st March in Viedma (northeast) ranged from 31,255 (5% quantile) to 35,856 $\text{GDH}_{10^\circ\text{C}}$ (95% quantile) with a median value of 33,893 $\text{GsGDH}_{10^\circ\text{C}}$. For the remaining sites, the energy

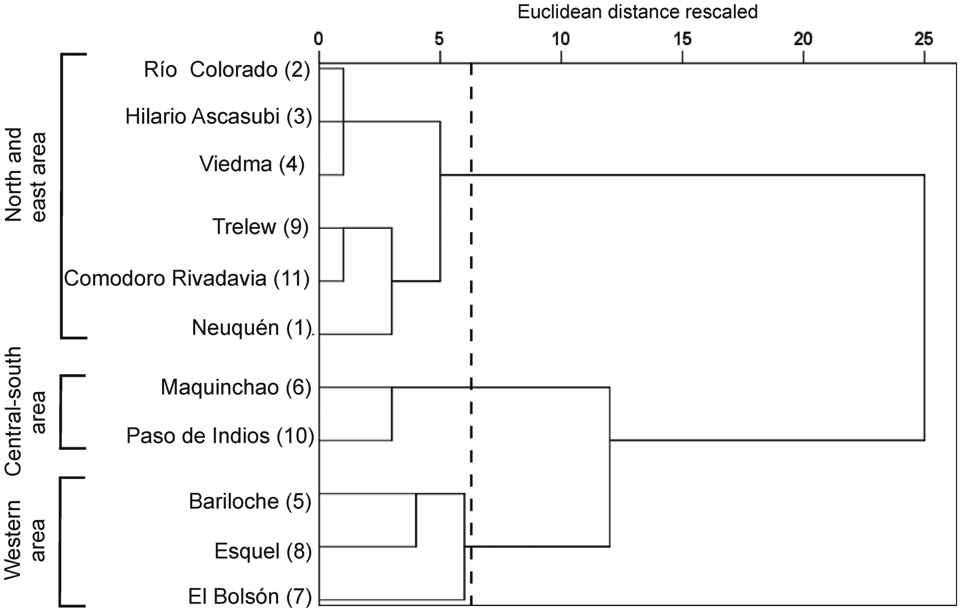

FIGURE 2 Grouping of 11 weather stations in North Patagonia produced by cluster analysis. The three clusters are based on agroclimatic conditions, with the cutoff point that defines the number of clusters determined by the "elbow" criterion (dashed line)

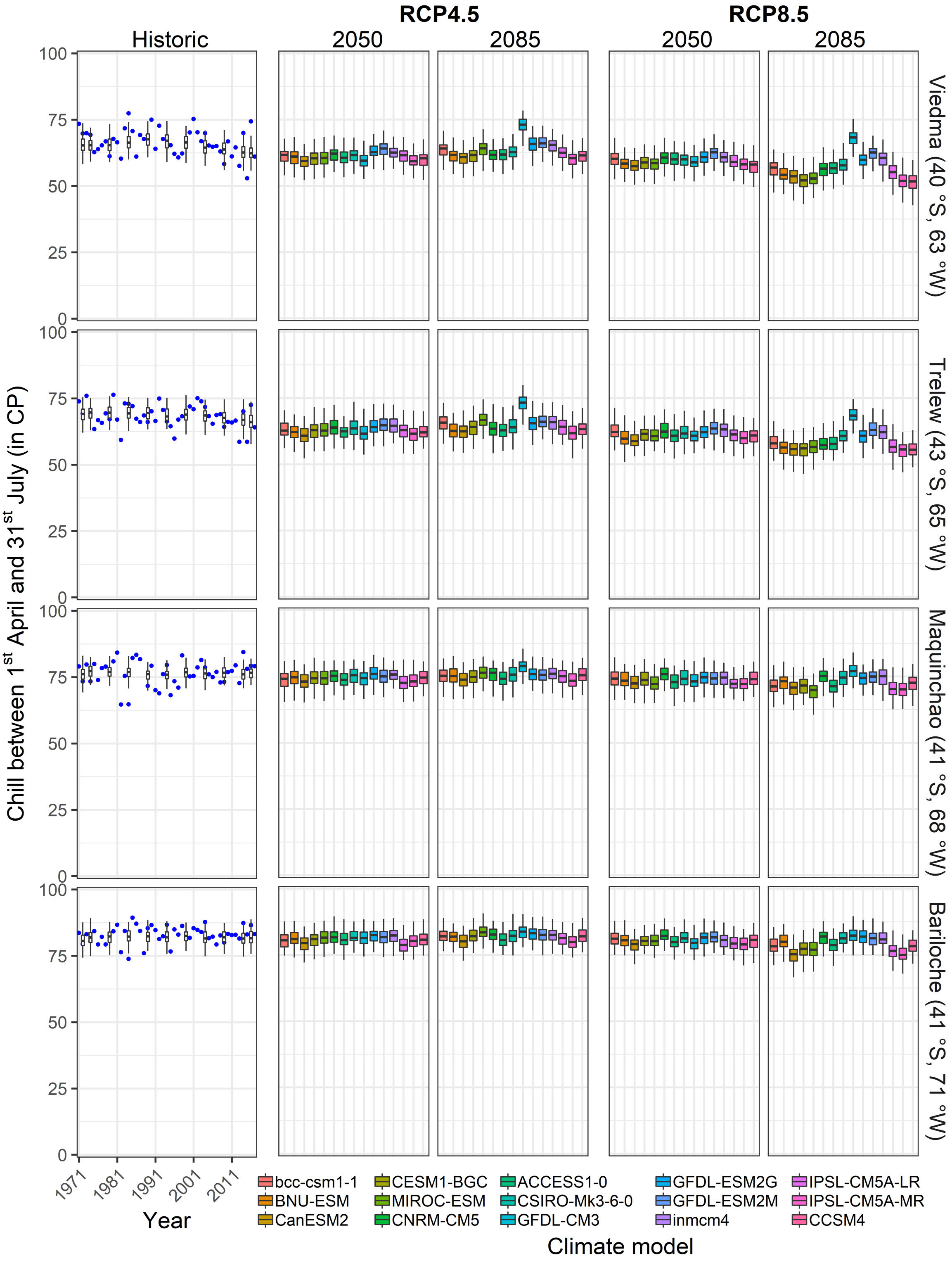

FIGURE 3 Historic and projected future winter chill availability in four sites of Argentinean Patagonia (Viedma, Trelew, Maquinchao and Bariloche). Chill was estimated as the number of Chill Portions accumulated between 1st of April and 31st of July. In the left hand "Historic" panels, dots represent the actual chill computed from the historic record and boxplots represent chill computed for the simulated historic weather scenarios. In future scenarios (RCP4.5 and RCP8.5 panels), boxplots represent the chill distribution forecasts according to the climate models. The left-to-right order for boxplots in future panels refers to the top-to-bottom order in climate model legend

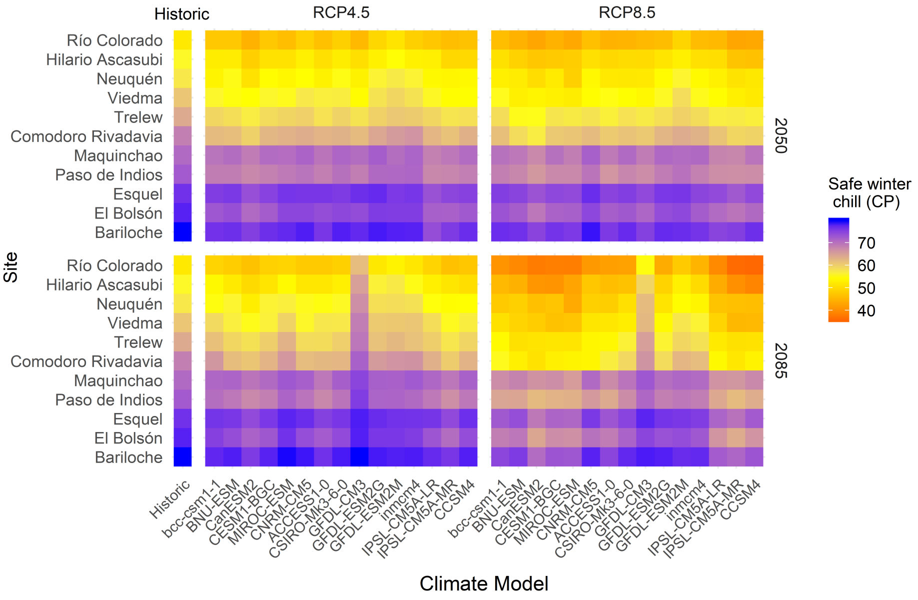

FIGURE 4 Safe Winter Chill estimations for 11 sites across North Patagonia for the historic record and for several future scenarios (using 15 climate models). Winter chill was estimated according to the Dynamic Model (in Chill Portions). Safe Winter Chill represents the first decile of the chill distribution, constituting a useful metric for chill risk analysis. For the historic scenario, Safe Winter Chill was computed using actual temperature records. Adapted from Fernandez *et al.* (2020). For figure interpretation, we refer to the electronic version of this article

availability reached 30,065–33,986 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ (5 and 95% quantiles) with a median of 32,779 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ in Trelew (east), 18,946–25,409 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ with a median of 22,465 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ in Maquinchao (central-south) and 12,058–17,898 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ with a median of 15,526 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ in Bariloche.

Historically observed data indicates increasing trends in growing season heat for all stations between 1970 and 2017, with increases of 174 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ per decade for Viedma ($p = .21$), 40 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ per decade for Trelew ($p = .86$), 319 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ per decade for Maquinchao ($p = .16$) and 762 $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$ per decade for Bariloche ($p < .01$). For future scenarios results show varying increases according to stations and across both RCP scenarios and years (Figure 5). Based on the median of the historically observed heat accumulation and the medians for the heat distributions projected by scenario ensembles for the RCP4.5 and RCP8.5 concentration pathways, heat (in $\mathrm{GsGDH}_{10^\circ\mathrm{C}}$) is expected to increase substantially over the 21st century. For the RCP4.5 scenario, expected increases were quantified at 5.8, 7.5, 12.5 and 22.6% for Viedma, Trelew, Maquinchao and Bariloche, respectively. For the RCP8.5 scenario, we expect greater heat increases amounting to 12.9% for Viedma, 15.3% for Trelew, 28.3% for Maquinchao and 52.1% for Bariloche, compared to the historically observed median of heat accumulation (Figure 5).

3.4 | Historical and prospective future spring frost prevalence

The risk of spring frost events, expressed here as the number of hours below 0°C between October 1st and November 30th ($\mathrm{SF}_{h<0^\circ\mathrm{C}}$), varied substantially across sites (Figure 6). For stations in the north and east, the 90% confidence level for the number of frost events for past scenarios ranged from 0 to 15 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$ for Viedma and from 0 to 17 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$ for Trelew, with median values of 2 and 0 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$, respectively. For Bariloche, we estimated a 90% confidence interval of 17–102 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$, with a median value of 54 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$. For Maquinchao, the confidence interval ranged from 3 to 84 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$, with a median of 29 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$. Historically observed trends were small for Viedma and Trelew, whereas Bariloche and Maquinchao showed decreasing frequencies of spring frost occurrence, which declined by between 1.5 and 3.0 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$ per decade over the past 47 years.

Across all future scenarios, spring frost risk is expected to decrease in all sites compared to the past. Viedma and Trelew are expected to remain low-risk locations for both RCP scenarios and reference years. In these sites no future scenario showed spring frost frequencies exceeding 6 $\mathrm{SF}_{\mathrm{h}<0^\circ\mathrm{C}}$ per year.

Compared to Viedma and Trelew, Maquinchao and Bariloche are expected to experience greater numbers of hours below 0°C during spring. Future scenarios indicated spring frost frequencies with 90% confidence intervals ranging from 4 to 63 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$ and 0 to 46 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$ in Maquinchao and 23 to 113 and 8 to 83 $\mathrm{SF}_{h<0^\circ\mathrm{C}}$ in Bariloche, for RCP4.5 by 2050 and RCP8.5 by 2085, respectively.

4 | DISCUSSION

For deciduous fruit trees, winter chill exposure is an important precondition for dormancy release and

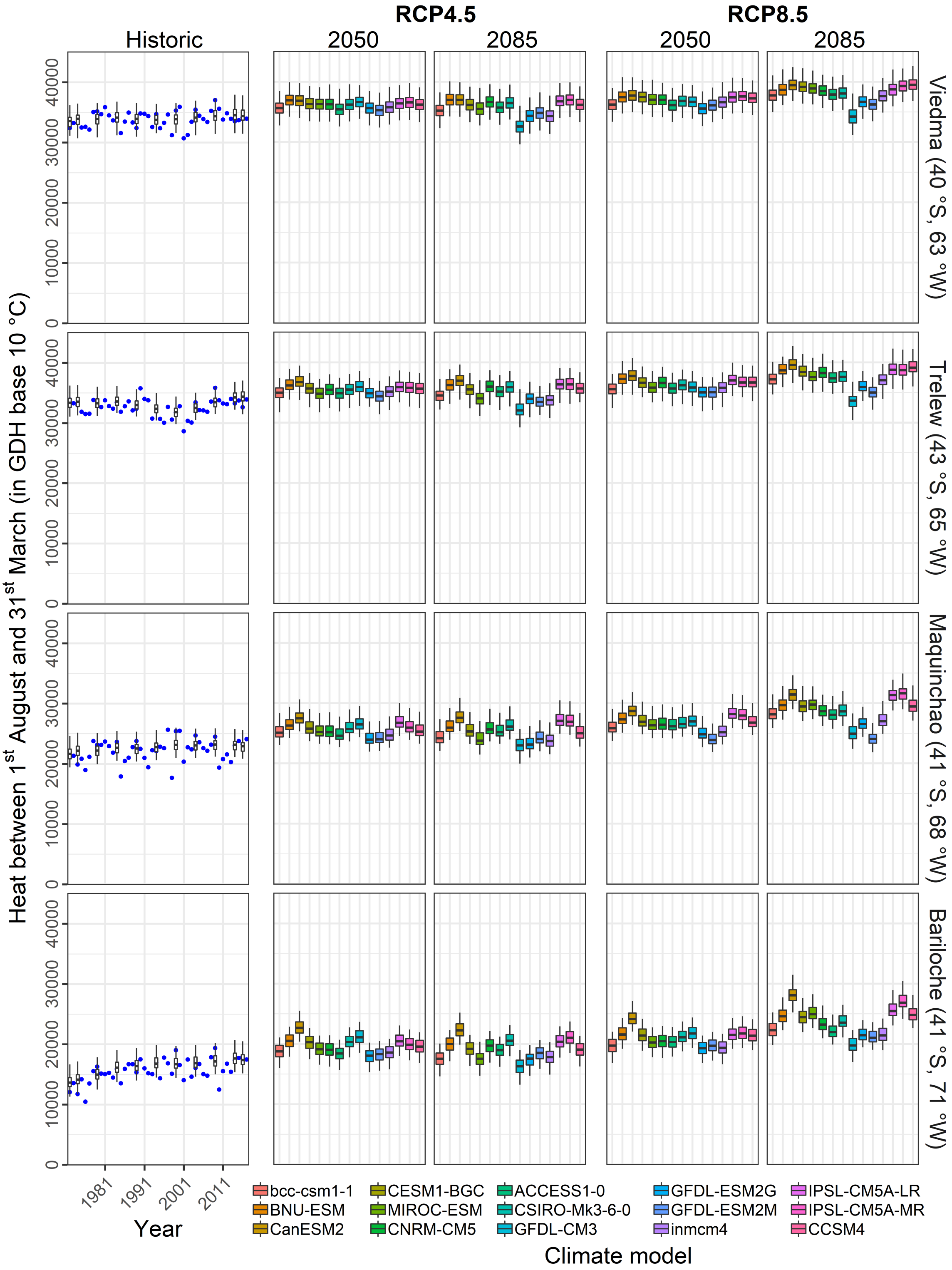

FIGURE 5 Historic and projected future heat accumulation (in Growing Degree Hours, using a base temperature of 10°C) between 1st of August and 31st of March in four locations in Argentinean Patagonia (Viedma, Trelew, Maquinchao and Bariloche). In the left hand "Historic" panel, dots represent the actual heat computed from the historic record and boxplots represent typical heat accumulation expectations computed from simulated historic weather scenarios. In future scenarios (RCP4.5 and RCP8.5 panels), boxplots represent the distribution forecasts according to the climate models. The left-to-right order for boxplots in future panels refers to the top-to-bottom order in climate model legend

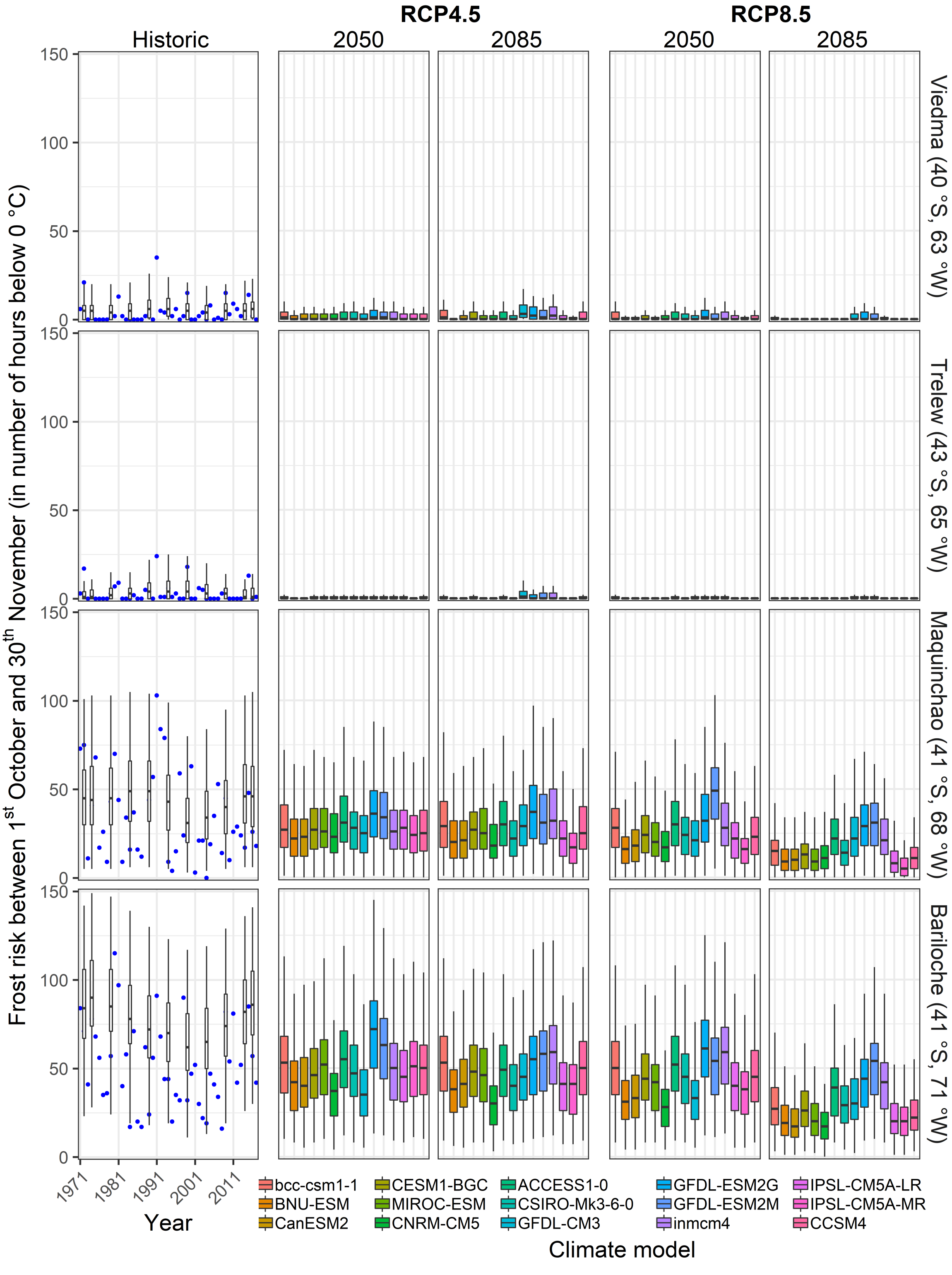

FIGURE 6 Historic and projected future number of spring frost occurrences (number of hours below 0°C) between 1st of October and 30th of November in four sites of Argentinean Patagonia (Viedma, Trelew, Maquinchao and Bariloche). In the left hand "Historic" panels, dots represent the actual spring frost computed from the historic record and boxplots represent the frost computed for the simulated historic weather scenarios. In future scenarios (RCP4.5 and RCP8.5 panels), boxplots represent the distribution forecasts according to the climate models. The left-to-right order for boxplots in future panels refers to the top-to-bottom order in climate model legend

successful spring bud burst and flowering (Campoy *et al*., 2012; Jones *et al*., 2015). Given this climatic requirement and the prospect of increasing temperatures due to global warming, fruit trees in many regions may soon experience – or may already be experiencing – situations where their ability to overcome their state of dormancy is compromised (Luedeling *et al*., 2011a; Darbyshire *et al*., 2013; Guo *et al*., 2015b; Campoy *et al*., 2019; Rodriguez *et al*., 2019).

The irrigated valleys of Patagonia's north and northeast are currently Argentina's main pear and apple production areas. This region also produces stone fruit (de Jong 2010) such as cherries (Cittadini and Pugh, 2004), and growers have recently begun introducing nuts – mainly walnuts and hazelnuts – and even some olive cultivars with high chilling requirements (Martín and Gallo, 2007; del Barrio and Martín, 2011; Martín *et al*., 2015). The future success of these tree crops is unlikely to be at risk in the coming decades, at least not because of declining winter chill.

We found that winter chill decreased slightly in North Patagonia between 1970 and 2017. This finding is consistent with previous estimates for this region contained in global (Luedeling and Brown, 2011), regional (Vincent *et al*., 2005) and local assessments (Rusticucci and Barrucand, 2004; Brendel *et al*., 2017). Many studies have concluded that chill declines are a direct consequence of global warming (Luedeling *et al*., 2009a; 2009b; 2009c; Farag *et al*., 2010; Cooke *et al*., 2012; Legave *et al*., 2013). However, we found that the extent to which chill decreases varies across the subregions and is generally of relatively low magnitude.

At present, the northern part of North Patagonia has enough winter chill even for fruit tree species and cultivars with high chilling requirements, but projected changes for the near future suggest some risk of chill shortfalls for high-chill cultivars. For future scenarios, winter chill projections by Global Climate Models indicate largely stable conditions, with the greatest average decreases in the number of Chill Portions expected at 16% in the northern and eastern agroclimatic clusters. At present, however, fruit tree production does not seem particularly threatened even in the northernmost part of the study region. If any problems arise at all throughout the 21st century, we expect adverse chill-related consequences only for high-chill cultivars in locations that are exposed to particularly severe warming.

In the western and central southern agroclimatic clusters (Bariloche and Maquinchao), future projections of chill availability, even for the most severe warming scenario, do not indicate chill losses greater than 6% compared to current conditions, which does not raise concerns about the viability of orchard operations. This finding confirms reports from other cool growing regions such as Germany (Luedeling *et al*., 2009a), where tree performance is expected to continue to depend more strongly on the effects of summer warming and late-spring frost risk than on conditions during chill accumulation (Okie and Blackburn, 2011).

Safe Winter Chill (Luedeling *et al*., 2009c) is a practical and powerful metric for selecting suitable tree cultivars and is closely aligned with the geographic subregions determined by cluster analysis. We expect the greatest challenges to production in the north, northeast and east of the study region (Figure 4). However, the currently high level of winter chill and the slow pace of chill decreases in the future lead us to conclude that fruit production in this region is unlikely to suffer strongly from chill deficiencies in the near to medium-term future.

Kramer *et al*. (2017) concluded that chilling and forcing temperature requirements are key traits determining how budburst dates in trees respond to temperature. For temperate and cold-temperate conditions such as those that characterize our study region, commercially successful fruit production thus does not only depend on environmental conditions that provide sufficient winter chill. It also requires subsequent spring warming to be gradual enough to avoid early budburst dates that may expose young sensitive plant tissue to the risk of frost damage (Okie and Blackburn, 2011).

At present, the northern, northeastern and eastern subregions provide sufficient growing-season heat for most temperate fruit trees to complete their annual development cycles. Historically observed growing season heat availability ($\text{GsGDH}_{10^\circ\text{C}}$) showed positive trends, with expected increases during the current century for all climate scenarios considered. Deciduous orchard areas around the Negro and Colorado River valleys, as well as the low valley of the Chubut River, may experience heat accumulation up to 38,000 $\text{GsGDH}_{10^\circ\text{C}}$, which should be sufficient for successful cultivation of all major fruit trees species usually grown in temperate climates (Hassankhah *et al*., 2017; Segura *et al*., 2017; Kaufmann and Blanke, 2019).

For the western, central and southern parts of our study region, where tree cultivation is currently limited by heat availability during the growing season, additional heat may allow the development of new production areas south of the current ones (Brendel *et al*., 2017). Although the historic baselines of heat availability differ between the Andean subregion, the western area and the central and southern plateaus of North Patagonia, all these subregions are likely to see increasing areas that are suitable for temperate fruit trees. The changing prospects for tree cultivation are anecdotally confirmed by a recent pilot project to explore replacement of traditional berry cultivation with orchards of late walnut cultivars, a development that, according to a local expert, was virtually unthinkable in the past (Eduardo Martinez, pers. comm.). Even though available heat on the central and southern plateaus is similar to the Andean subregion, orchard development is likely to remain constrained by lack of water for supplementary irrigation, which is considered a critical requirement for tree crop production in this extensive subregion.

We expect the risk of spring frost to decrease throughout North Patagonia, in particular across the north, northeast and east of the study region. We also projected decreases for the western and south-central regions, but not to an extent that might fundamentally change orchard exposure to frost risk. Orchard developments in this region are likely to remain dependent on active frost protection methods to alleviate the risk of economically harmful crop losses due to spring frost. Besides the influence of the geographic zone on frost risk, previous studies suggest a relationship among atmospheric circulations such as ENSO cycles and the occurrence and duration of winter frost events in humid areas of the Pampas in Argentina (Müller *et al.*, 2003; Müller and Berri, 2007). A recent regional study suggested that frost rings, obtained by dendroclimatology analyses in *Araucaria araucana* (Molina) K. trees in northern Patagonia, were associated with "La Niña" years (Hadad *et al.*, 2019). On the contrary, "El Niño" years are associated with a generally lower number of annual frost events. Additional research would help to better understand the relationship of ENSO cycles and spring frost risk and facilitate its integration into new forecasting efforts.

A number of studies analysing the possible effects of warmer temperatures on forest tree phenology have highlighted increased frost risk due to earlier bud break dates. In temperate places, such as the southeastern United States, where chill accumulation is usually sufficient to fulfil chilling requirements, increasing temperature in late winter may lead to false spring events and trigger bud break (Marino *et al.*, 2011; Augspurger, 2013). This may greatly increase the risk of frost events. In temperate fruit trees, however, the extent (Martinez-Lüscher *et al.*, 2017) as well as the direction (Guo *et al.*, 2015a) of such phenological shifts remains unclear. Our findings show that in temperate or cold-temperate zones such as North Patagonia, climate change is expected to increase heat availability. This can improve fruit maturation and potentially reduce the occurrence and severity of frost events if bloom dates remain largely unchanged. It may also alleviate critical risks faced by tree growers in such environments. Nonetheless, further research is required to decipher the effect of global warming on bloom dates of temperate fruit trees, and the risk of frost events.

With this study, we aim to equip growers in North Patagonia with information that allows them to anticipate future growing conditions, so that they can – if necessary – adjust their orchard management strategies and possibly explore new opportunities that may arise in the future. Our results show that future chill and heat accumulation, as well as the risk of spring frost, are not entirely unpredictable but likely to fall within relatively well-confined ranges that can be used as a basis for strategic planning. We hope that such projections of future agroclimatic conditions will enable researchers and policy-makers to set in motion the long-term preparatory activities, in terms of exploratory studies and agricultural development strategies, that will allow growers to exploit the new opportunities that climate change may bring to North Patagonia's fruit production industry.

5 | CONCLUSIONS

Climate change appears to be moving agriculture's southern frontier and changing the agricultural prospects for North Patagonia. Even though our projections indicate regional variation in future availability of chill and heat, as well as in the exposure to spring frost risk, we expect improvements in the climatic suitability for tree crops of temperate-zone origin across the entire region.

While we anticipate a slight decrease in chill availability among the warmer locations we investigated, these changes seem unlikely to challenge the tree cultivars that have traditionally been cultivated. Increasing heat availability, on the other hand, may create opportunities for growers to introduce new species and cultivars to the region. Since spring frost is likely to remain a common occurrence, especially in the southern and continental parts of North Patagonia, such introductions will have to carefully consider how the chilling and heat requirements of new germplasm are attuned to local agroclimatic conditions. Our results provide a basis for planning such introductions and for enabling growers to exploit new opportunities for producing pears, apples, cherries and other temperate fruit and nut crops beyond their traditionally suitable ranges.

CONFLICT OF INTEREST

The authors confirm that this research was developed in the absence of any relationship that can lead to a possible conflict of interest.

ORCID

Ricardo del Barrio https://orcid.org/0000-0003-2968-0583
Eduardo Fernandez https://orcid.org/0000-0002-6949-9685
Andrea S. Brendel https://orcid.org/0000-0002-0909-

4694

Cory Whitney https://orcid.org/0000-0003-4988-4583
José A. Campoy https://orcid.org/0000-0002-6018-5698
Eike Luedeling https://orcid.org/0000-0002-7316-3631

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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