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Warm nights in the Argentine Pampas: Modelling its impact on wheat and barley shows yield reductions

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ABSTRACT

Efforts to anticipate how climate change and variability will affect future crop production can benefit from understanding the impacts of current and historic changes. This study aimed to quantify and compare the impact of increased night temperature on potential yield and phenology of wheat (*Triticum aestivum L.*) and barley (*Hordeum vulgare L.*) crops modelled using APSIM with historical climate series (1961–2014) in sites representative of the Argentinean Pampas. For each site, the sowing date was adjusted to avoid frost and heat events at flowering, based on historical probability. The critical period was the more sensitive crop phase (shortened by 0.6 d decade^{-1}) for the observed asymmetric warming; regional minimum temperature trend of ca. 0.14 and 0.16 °C decade^{-1} in wheat and barley, respectively. Wheat and barley yields declined across the region between ca. 2% and 9% per °C increase in the minimum temperature during the critical period, linked to lower cumulative radiation capture as a result of a shorter crop phase and lower incident radiation due to displacement towards winter. Regional variability in the simulated yield response to the observed night warming was mainly explained by differences the response of incident solar radiation during the critical period to the minimum temperature increase.

1. Introduction

Temperature is the variable more affected by climate change with a long-term asymmetric warming due to higher night temperatures and more frequent extreme events being key features of this phenomenon (IPCC, 2014). Its impact on crop production is the main source of uncertainty in current and future climate scenarios (Lobell and Burke, 2008). Two agronomically relevant, though not necessarily independent, processes are affected by warming scenarios. Higher temperatures in the non-stressful range shorten the crop cycle, while temperatures in the stressful range can disrupt reproduction, whereas crop growth is directly or indirectly affected by both temperature ranges (Sadras and Dreccer, 2015). Efforts to anticipate how climate change and variability will affect future food availability can benefit from understanding the impacts of current and historic changes (Lobell et al., 2011).

Wheat (*Triticum aestivum L.*) and barley (*Hordeum vulgare L.*) are the main temperate cereals in Argentina, strategically important for the sustainability of the farming system, covering around 20% of the cropping area (ca. 25 Mha; Agroindustria, 2016). Their stubble volume, composition and cover during winter have a positive impact on soil C balance, reducing erosion risk and facilitating the management of temperate weeds in a non-tillage system strongly dominated by soybean crops (Satorre, 2011). Other benefits include lowering spring flooding risk due to raising water tables (Mercau et al., 2016) and potential improvement in productivity per unit area per year as part of a double cropping scheme (Andrade and Satorre, 2015).

Above 90% of ca. 12 wheat Mt and the majority of ca. 4 barley Mt produced every year in Argentina originate in the Pampas region (Agroindustria, 2016), one of the most important grain producing areas in the world (Hall et al., 1992). Detailed descriptions of weather, soils, and cropping systems of the Pampas can be found in Hall et al. (1992),

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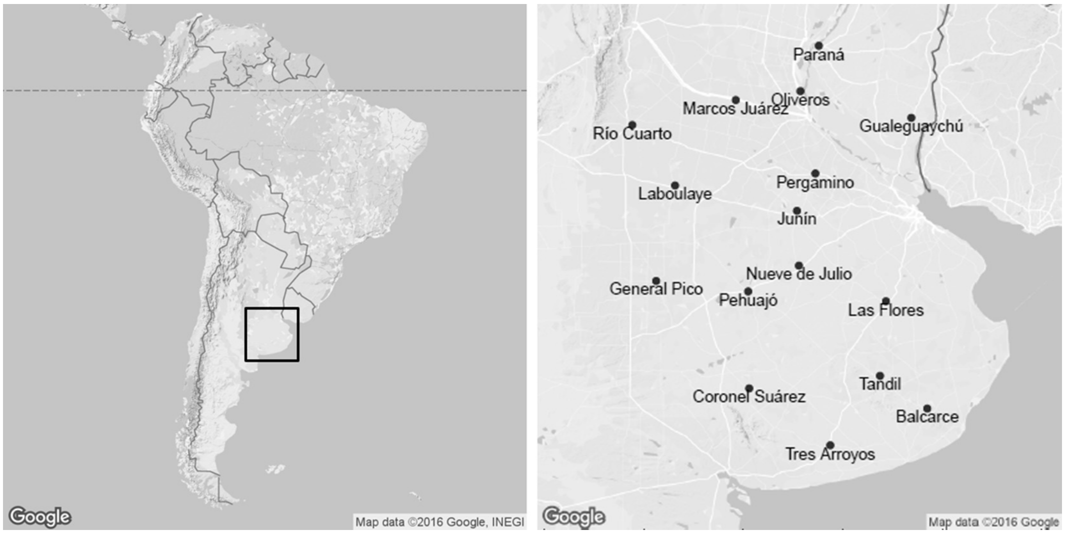

Fig. 1. The Argentine Pampas, sites chosen to evaluate wheat and barley crops response to high night temperatures.

Calviño and Monzon (2009) and Satorre (2011). Briefly, the Pampas is mostly a flat area in central-eastern Argentina, extending ca. 52 Mha from 31° to 39° South latitude and from 57° to 65° West longitude. Regional climate is temperate humid, without a dry season and with a very hot summer. Average temperature increases in a South-North transect (annual mean temperature range from 14 °C to 17 °C); however, thermal amplitude increases from East to West with distance to the ocean. Annual rainfall diminishes from East to West from 1000 to 500 mm with an isohigrous regime. Soils are Mollisols, formed over loessic sediments. Internal variability needs to be recognized when analysing the response of crops to temperature. In the Pampas, a retrospective analysis reported a mean temperature warming of ca. 0.5 °C between 1960 and 2010 and projections indicated warmings between 0.5 and 1 °C for the near future (2015–2039) and between 0.5 and 3.5 °C for the end of the Century (2075–2099), varying according to the emission scenario considered (Barros et al., 2015). Minimum temperature increased at a faster rate than maximum temperature during the last decades in the Pampas (Barros et al., 2015; Fernández-Long et al., 2013; Rusticucci, 2012), in line with the asymmetric warming observed in other growing regions (Easterling et al., 1997; Rao et al., 2015; Sillmann et al., 2013; Vose et al., 2005). Hence this paper is focused on the effects of asymmetric warming on wheat and barley production in the Pampas.

The design of crop adaptation strategies to high night temperature will rely on knowledge of the crop response to environmental modifications (Asseng et al., 2015; Fischer et al., 2014). In recent studies on the effect of a direct increase in night temperature, an accelerated development and shortened crop duration were the main drivers behind the negative response of wheat and barley yield to warm nights both during the grain number determination and grain filling periods (García et al., 2015; García et al., 2016). Yield reduction was ca. 7% $°C^{-1}$ of night temperature increase when warming occurred during the critical period (García et al., 2015), while night warming during the grain filling period reduced yield ca. 4% $°C^{-1}$ (García et al., 2016), similarly for wheat and barley. Confirming the impact of temperature, maximum on-farm rainfed yields (2003–2008) were related to low spring temperatures ($<$ 18.3 °C), following a high photo-thermal quotient during reproductive stages (Andrade and Satorre, 2015). Simulation studies have also have evaluated the impact of mean temperature and solar radiation on potential yield determination in wheat at regional level, both in current (Magrin et al., 1993; Menéndez and Satorre, 2007) and/or future scenarios (Magrin et al., 2005; Magrin et al., 2009; Ortiz de Zárate et al., 2015). Most studies cover the grain number determination and filling period focusing on the October–November period in the Rolling Pampas (Magrin et al., 2009) and October–December in the Southern Pampas (Monzon et al., 2007). For the Rolling Pampas, Magrin et al. (2009) showed reductions of 7% $°C^{-1}$ in simulated wheat potential yield due to an increase in October–November minimum temperature during the 1931–2000 period. Sadras and Monzon (2006) calculated that the rise in minimum temperature could result in a shortening of pre-flowering phases by a week $°C^{-1}$. A follow-up study by Monzon et al. (2007) confirmed this trend and calculated an advancement in harvest date by 0.15 d yr^{-1} in the Southern Pampas,though no impact on simulated water-limited yield. Wheat and barley yield response to temperature with emphasis on night temperature variations has not been evaluated in detail before.

This study aimed to quantify and compare the impact of increased night temperature on wheat and barley crops during the grain number determination period using the Agricultural Production Systems sIMulator v 7.7 (APSIM, Holzworth et al., 2014; Keating et al., 2003) and historical climate series for sites representative of the Pampas. The study (i) analysed climate trends, firstly seasonally and then specifically during the critical period determined by simulated flowering date, and (ii) simulated potential yield response to temperature across the Pampas.

2. Methodology

2.1. Representative sites of the Pampas and historical climate series

The study was performed for 16 sites across the Pampas (Fig. 1) chosen based on their production volume (Agroindustria, 2016) and availability of long term daily climate records comprising maximum and minimum temperature, rainfall and solar radiation from 1961 to 2014 collected by public Argentinean agencies such as the National Meteorological Service and the National Agricultural Research Institute. Quality of these climate records was performed by the Regional Climate Centre for Southern South America (CRC-SAS, 2016), with purposedly developed methodologies (http://www.crc-sas.org/es/guias_crc.php).

2.2. Simulation of wheat and barley phenology and yield using APSIM with historical climate series

Wheat and barley crop simulations were performed with APSIM. The wheat and barley modules of APSIM have been widely validated in different growing areas around the world (Asseng et al., 1998; Asseng et al., 2012; Asseng et al., 2000; Zhang et al., 2012).

Table 1

Coordinates, soil type (Soil Survey Staff, 2014), wheat and barley sowing date based on the calculated optimal flowering date, and average values of minimum (Tn) and maximum (Tx) temperature and incident solar radiation (SR) for the September-October-November (SON) season during 1961–2014 period, for each representative site in the Pampas. Northern and southern sites are separated by a line (see item 2.2).

Site	Latitude	Longitude	Altitude (masl)	Soil type	Sowing date		Optimal flowering date	SON		
					Wheat	Barley		Tn (°C)	Tx (°C)	SR (MJ m^{-2} d^{-1})
Paraná	-31.78	-60.48	78	Aquic Argiudoll	11-May	01-Jun	21-Sep	12.4	24.4	20.5
Oliveros	-32.55	-60.85	26	Vertic Argiudoll	26-May	16-Jun	06-Oct	11.8	24.2	20.0
Marcos Juárez	-32.7	-62.15	114	Typic Argiudoll	26-May	21-Jun	10-Oct	10.7	24.8	19.6
Gualeguaychú	-33	-58.62	21	Argillic Chromic Paludert	21-May	06-Jun	01-Oct	11.6	23.7	18.5
Río Cuarto	-33.12	-64.23	421	Typic Haplustoll	06-May	26-May	27-Sep	11.1	23.7	18.9
Pergamino	-33.93	-60.55	65	Typic Argiudoll	21-May	16-Jun	13-Oct	10.1	23.1	19.9
Laboulaye	-34.13	-63.37	137	Udorthentic Haplustoll	16-May	11-Jun	10-Oct	9.9	24.1	20.2
Junín	-34.55	-60.92	81	Typic Argiudoll	26-May	21-Jun	16-Oct	9.8	22.7	19.4
Nueve de Julio	-35.45	-60.88	76	Thapto Argic Hapludoll	21-May	16-Jun	15-Oct	10.0	22.7	19.6
General Pico	-35.7	-63.75	145	Entic Haplustoll	01-Jun	26-Jun	21-Oct	9.7	23.5	16.4
Pehuajó	-35.87	-61.9	87	Typic Hapludoll	06-Jun	01-Jul	26-Oct	9.4	22.1	19.5
Las Flores	-36.03	-59.13	36	Thapto Argic Hapludoll	26-Jun	16-Jul	04-Nov	8.5	21.5	19.1
Tandil	-37.23	-59.25	175	Typic Argiudoll	26-Jun	21-Jul	13-Nov	7.1	19.8	18.4
Coronel Suárez	-37.43	-61.88	233	Typic Argiudoll	11-Jul	21-Jul	17-Nov	6.8	20.5	19.6
Balcarce	-37.75	-58.3	130	Typic Argiudoll	21-Jun	16-Jul	12-Nov	7.4	19.3	18.7
Tres Arroyos	-38.33	-60.25	109	Typic Argiudoll	16-Jun	11-Jul	06-Nov	7.9	20.4	18.4

The wheat cultivar ‘Baguette 601’ and the barley cultivar ‘Scarlett’ were simulated because their crop cycle duration is potentially adaptable to all sites (Fig. 1) and the abundance of crop phenology and yield data available for calibration and validation in the Pampas. ‘Baguette 601’ is a high-yielding intermediate maturity Argentinean cultivar (INASE, 2016); while ‘Scarlett’ is an intermediate maturity barley cultivar, topping the adoption ranking during the last decade (Alzueta et al., 2014; INTA, 2016). ‘Baguette 601’ and ‘Scarlett’ were calibrated based on reference cultivars available in APSIM v7.7, adjusting 3 and 5 genotype parameters respectively (Supplementary Table 1). Calibrated cultivars were validated using independent experimental data from national variety trials (INASE, 2016; INTA, 2016). Simulated wheat and barley flowering time (i.e. sowing-anthesis - DC0-DC65, Zadoks et al., 1974) and yield had acceptable precision with errors (nRMSE) of ca. 3% in phenology and 10% in yield (Supplementary Fig. 1).

Crop simulations were performed in the 16 sites across the Pampas listed in Table 1 using weather data from 1961 to 2014, with the representative soil for each site under irrigation (available soil water maintained close to 100%) and non-limiting N supply (fertilization to keep 100 kg N ha^{-1} available in the 3 upper layers of soil profile). The crop was sown at 50 mm depth, at a density of 300 plants m^2 and 0.175 m of row spacing, following current practices. For each site, the “optimal” sowing date was chosen as the one that, on average for 1961–2014, simulated flowering date (DC65) in a “low risk window” for frost and heat events based on historical probability, following Zheng et al. (2012) with modified thresholds for temperature and risk levels (Supplementary Fig. 2). The “optimal” sowing date was chosen among 20 sowing opportunities per site and year simulated from May 1st to August 6th (5–6 d intervals) to cover the entire sowing window used in the Pampas. The last frost day was defined as the last day of the year with a minimum air temperature lower or equal to 2 °C (Frederiks et al., 2015), and the first heat day as the first day after 1st July with a maximum air temperature equal or $>$32 °C (Wardlaw and Wrigley, 1994). The Pampas region was divided in consultation with local agronomists into northern and southern sites (Table 1) as different frost and heat risk criteria are adopted in each sub-region. In southern sites, frost and heat low risk thresholds were defined as the 75th percentile of last frost day and 30th percentile of first heat day (i.e. low risk window for flowering is the ranges from when there is $<$25% chance of frost and $<$30% chance of heat for 1961–2014), targeting flowering date as the frost threshold date by prioritized earlier flowering and higher potential yield (Menéndez and Satorre, 2007), allowing earlier sowing of the summer crop in double cropping system (Monzon et al., 2007). In northern sites, frost low risk threshold was the 80th percentile, heat threshold remained the same and optimal flowering date was the average date between frost and heat low risk thresholds. Unlike wheat, barley anthesis normally occurs before heading (DC59). It is at this last crop stage that the greatest vulnerability to frost and heat occurs. Therefore, the optimal flowering date calculated for barley was corrected by advancing it by 5 or 7 days in northern and southern sites respectively.

Crop stages of emergence (DC11), anthesis (DC65) and physiological maturity (DC90), and yield were extracted from APSIM wheat and barley simulations performed with the optimal sowing date in each season and site. The grain number determination period known as “critical period” was then calculated as the time (d) between 300 °Cd before and 100 °Cd after simulated DC65 (Dreccer et al., 2007), using a base temperature of 4.5 °C (Fischer, 1985), in both crops. The whole crop cycle was then divided into: (i) a crop establishment and tillering phase, from DC11 to the beginning of the critical period (i.e. 300 °C pre-anthesis), (ii) the critical period, and (iii) the effective grain filling period, from the end of critical period (i.e. 100 °C post-anthesis) to DC90.

2.3. Seasonal and phenology driven analysis of historical climate

Climate analysis was undertaken for both season and simulated crop phases. Seasonal analysis focused on September-October-November (SON) season as it covers both the grain number determination and grain filling period of most wheat and barley crops in the Pampas (Calviño and Monzon, 2009; Menéndez and Satorre, 2007). Climate variables were then averaged accordingly. Temperature variation during 1961–2014 was evaluated by means of linear trends (°C decade^{-1}) (Eq. (1)), i.e. the slope of temperature-year relationship ($\partial T/\partial yr$, °C yr^{-1}). The slope was extracted by linear regression analysis.

$$\text{Temperature trend } (^{\circ}C\ decade^{-1}) = (\partial T/\partial yr)^{*}10 \tag{1}$$

For the phenology driven analysis, averages of maximum, minimum and mean temperatures and cumulative and average of incident solar radiation were calculated for each simulated wheat or barley crop phase. Means of linear trends (°C decade^{-1}) for the whole crop cycle and each phase were also calculated (Eq. (1)).

2.4. Crop response to historical minimum temperature variations

The response of simulated yield, critical period duration and cumulative solar radiation during that phase in response to observed minimum temperature in the same period were estimated in two steps. Firstly, to compare sites, each simulated crop trait (SCT) was calculated as a value relative ($SCT_{r.CS}$) to the average of each crop and site across the complete climate record 1961–2014 ($SCT_{\overline{X}\cdot CS}$) (Eq. (2)).

$$SCT_{r\cdot CS} = SCT\ (trait\ unit)/SCT_{\overline{X}\cdot CS}(trait\ unit) \tag{2}$$

Secondly, the relative value of the crop trait ($SCT_{r.C_{*}S}$) was plotted against observed minimum temperature and the response ($\partial SCT_{r\cdot CS}/\partial Tn$, $°C^{-1}$) calculated as the slope extracted by linear regression analysis (Eq. (3)).

$$Response\ (\%\ °C^{-1}) = (\partial SCT_{r\cdot CS}/\partial Tn)^{*}100 \tag{3}$$

Similarly to temperature trends (Eq. (1)), inter-annual variations in simulated wheat and barley yield and phenology during the 1961–2014 period were evaluated by linear trends (t ha^{-1} decade^{-1} or d^{-1} decade^{-1}, respectively) (Eq. (4)), i.e. the slope of the simulated crop trait -year relationship ($\partial SCT/\partial yr$, t ha^{-1} yr^{-1} or d^{-1} yr^{-1}).

$$SCT\ trend\ (t\ ha^{-1}\ decade^{-1}\ or\ d^{-1}\ decade^{-1}) = (\partial SCT/\partial yr)^{*}10 \tag{4}$$

3. Results

3.1. Observed temperature trends in the Pampas and its impact on simulated crop yield and phenology

Positive trends for average mean temperature during the SON season (from 0.02 to 0.49 °C decade^{-1}) were observed in 15 of the 16 representative sites of the Pampas, 13 of which were statistically significant (Fig. 2a). At a regional scale, observed changes in mean temperature were better explained by variation in minimum than maximum temperature (Fig. 2b,c). The range of change in both extreme temperatures was similar in absolute terms, which translated in temperature increasing by ca. 2% decade^{-1} in the case of the minimum and only by ca. 1% decade^{-1} in the case of the maximum temperature. The minimum and maximum temperatures trends (Eq. (1)) were not associated ($p = 0.22$). On average, observed spring temperature trends in the Pampas were 0.22, 0.24 and 0.20 °C decade^{-1} for mean, minimum and maximum temperature, respectively. Two sites in the southern part of the Pampas, Coronel Suárez and Tandil, stood out as presenting no significant change in mean temperature (Fig. 2a). In fact, in Coronel Suárez, significant negative trends for minimum temperature were observed (−0.15 °C decade^{-1}, $p = 0.04$). On the other hand, only in Laboulaye, a northern site where mean temperature did not vary significantly, minimum temperature increased (0.17 °C decade^{-1}, $p = 0.02$) but maximum temperature remained unchanged.

The main results from wheat and barley crop simulations performed with APSIM as average of 54 growing seasons are described in Table 2. Simulated yield tended to be higher in wheat than barley (7.6 vs. 7.3 t ha^{-1}, averaged for the whole region), with a regional variability of ca. 40% of the mean overall years and locations in both crops. The adjusted sowing date based on the low risk window for flowering date (Table 1) resulted in a duration of the critical period ranging from 33 to 38 d in wheat and 35 to 41 d in barley, with no latitudinal trend, with mean temperature ranging from 14.8 to 16.2 °C in wheat and 14 to 15.6 °C in barley. On average for both crops, regional variability around the variable mean was 15% in the simulated duration of the critical period duration, 17% in the minimum and 11% in the maximum observed average temperatures during that phase. Average daily incident solar radiation observed during the critical period was the climate variable showing higher regional variation (ca. 44% of the mean), increasing from N to S.

Simulated wheat and barley yield tended to decrease during 1961–2014 in a large proportion of the Pampas' sites (Fig. 3, upper panel). On average, higher yield reductions occurred in southern sites with greater potential yield (Table 2), ca. 250 and 200 kg ha^{-1} decade^{-1} in wheat and barley, respectively. In two northern sites, Laboulaye and Nueve de Julio, wheat and barley yield tended to increase during the 54 years analysed. In line with the positive trends observed for seasonal temperatures (Fig. 2), simulated crop phases tended to shorten in most sites of the Pampas during the last 5 decades (Fig. 3, middle panel). On average, the duration of the wheat and barley crop cycle was reduced ca. 1 d decade^{-1}. Two sites deviated from this trend, Oliveros, where the crop cycle shortened > 2 d decade^{-1}, and Laboulaye, where the crop cycle was not reduced. Crop cycle shortening was strongly associated with earlier flowering ($r > 0.9$, $p < 0.01$ for both crops) due to a shorter critical period (Fig. 3, bottom panel). On average for the whole region and both crops,

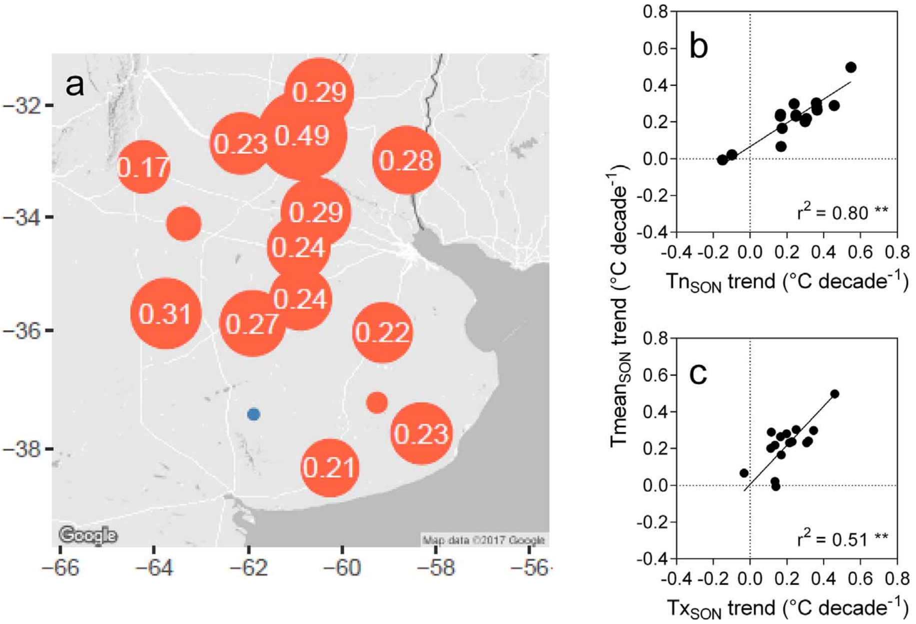

Fig. 2. Observed temperature trends in the September-October-November (SON) season during 1961–2014 period in the Pampas. (a) Average mean temperature (Tmean_{SON}) trends. Circle size and colour correspond to change in magnitude (°C decade^{-1}) and direction (red: increase, blue: decrease), respectively. Only statistically significant values ($p < 0.05$) are indicated. Longitude and latitude are indicated by y and x axes, respectively. Relationship between Tmean_{SON} trends and average (b) minimum (Tn_{SON}) and (c) maximum temperatures (Tx_{SON}) trends. Regression coefficient (model II) and the corresponding significant probability (**: $p < 0.01$, *: $p < 0.05$) are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Simulated yield and critical period duration of wheat and barley crops using APSIM v7.7 in representative soils and optimal sowing dates (details in Table 1), and critical period averaged minimum (Tn) and maximum (Tx) temperature and incident solar radiation (SR) during 1961–2014 for sites in the Pampas (ordered from North to South). Value mean and standard error are indicated in each case. Northern and southern sites are separated by a line (see item 2.2). The critical period started 300 °Cd before and finished 100 °Cd after (base temperature 4.5 °C) simulated DC65.

Site	Wheat					Barley				
	Yield (t ha^{-1})	Critical period				Yield (t ha^{-1})	Critical period			
		Duration (d)	Tn (°C)	Tx (°C)	SR (MJ m^{-2} d^{-1})		Duration (d)	Tn (°C)	Tx (°C)	SR (MJ m^{-2} d^{-1})
Paraná	6.3 ± 0.1	37 ± 1	9.3 ± 0.2	21.1 ± 0.2	15.7 ± 0.2	6.0 ± 0.1	37 ± 1	9.2 ± 0.2	20.9 ± 0.1	15.6 ± 0.2
Oliveros	7.3 ± 0.1	34 ± 1	9.8 ± 0.2	22.0 ± 0.2	16.8 ± 0.2	7.0 ± 0.1	36 ± 1	9.3 ± 0.2	21.6 ± 0.2	16.3 ± 0.2
Marcos Juárez	7.3 ± 0.1	34 ± 1	8.9 ± 0.2	23.0 ± 0.2	17.3 ± 0.3	7.1 ± 0.1	35 ± 1	8.5 ± 0.2	22.7 ± 0.2	16.8 ± 0.2
Gualeguaychú	6.1 ± 0.1	36 ± 1	9.6 ± 0.2	21.3 ± 0.1	14.8 ± 0.3	6.2 ± 0.1	38 ± 1	8.9 ± 0.2	20.7 ± 0.1	14.1 ± 0.2
Río Cuarto	7.5 ± 0.1	38 ± 1	8.4 ± 0.2	21.2 ± 0.2	15.7 ± 0.2	7.4 ± 0.1	40 ± 1	8.0 ± 0.1	20.8 ± 0.2	15.3 ± 0.2
Pergamino	8.3 ± 0.2	37 ± 1	8.6 ± 0.2	21.5 ± 0.2	17.9 ± 0.3	8.1 ± 0.2	39 ± 1	8.3 ± 0.2	21.1 ± 0.2	17.5 ± 0.3
Laboulaye	7.9 ± 0.1	36 ± 1	8.2 ± 0.2	22.6 ± 0.2	18.0 ± 0.2	7.7 ± 0.1	37 ± 1	7.8 ± 0.2	22.2 ± 0.2	17.4 ± 0.2
Junín	7.9 ± 0.1	36 ± 1	9.0 ± 0.2	21.7 ± 0.2	18.0 ± 0.3	7.3 ± 0.1	38 ± 1	8.4 ± 0.2	21.1 ± 0.2	17.3 ± 0.2
Nueve de Julio	8.0 ± 0.1	37 ± 1	9.1 ± 0.2	21.4 ± 0.2	18.2 ± 0.3	7.2 ± 0.1	38 ± 1	8.6 ± 0.2	20.8 ± 0.1	17.5 ± 0.2
General Pico	6.3 ± 0.2	33 ± 1	9.5 ± 0.1	22.9 ± 0.2	16.3 ± 0.3	5.7 ± 0.2	36 ± 1	8.6 ± 0.1	22.2 ± 0.2	15.2 ± 0.3
Pehuajó	8.0 ± 0.1	35 ± 1	9.6 ± 0.2	22.0 ± 0.2	19.4 ± 0.2	7.7 ± 0.1	37 ± 1	8.9 ± 0.2	21.3 ± 0.2	18.5 ± 0.2
Las Flores	7.9 ± 0.1	34 ± 1	9.6 ± 0.2	22.3 ± 0.2	20.4 ± 0.2	7.7 ± 0.1	37 ± 1	8.9 ± 0.2	21.5 ± 0.2	19.2 ± 0.3
Tandil	7.7 ± 0.1	37 ± 1	8.6 ± 0.2	21.6 ± 0.2	21.3 ± 0.2	7.2 ± 0.1	40 ± 1	8.1 ± 0.1	20.8 ± 0.2	20.3 ± 0.2
Coronel Suárez	9.2 ± 0.1	34 ± 1	8.9 ± 0.2	22.9 ± 0.2	23.0 ± 0.3	8.6 ± 0.1	39 ± 1	7.9 ± 0.1	21.4 ± 0.2	21.5 ± 0.2
Balcarce	7.9 ± 0.2	38 ± 1	8.7 ± 0.1	20.9 ± 0.2	21.1 ± 0.3	7.3 ± 0.1	41 ± 1	8.1 ± 0.1	19.9 ± 0.1	19.8 ± 0.3
Tres Arroyos	8.0 ± 0.1	36 ± 1	9.0 ± 0.1	21.6 ± 0.2	20.4 ± 0.2	7.9 ± 0.1	40 ± 1	8.3 ± 0.1	20.5 ± 0.2	19.0 ± 0.2

the phases of crop establishment and tillering period, critical period, and effective grain filling period were shortened ca. 0.1, 0.6 y 0.2 d decade^{-1}. In fact, the first crop phase was lengthened in some northern sites.

Observed temperature patterns in the SON season were confirmed and could be further dissected in the phenology driven climate analysis, both for wheat and barley (Fig. 4). Observed average mean temperature trends, both during the simulated whole crop cycle and the critical period, were better explained by minimum than maximum temperature trends. Regional ranges of temperature trends were higher in minimum

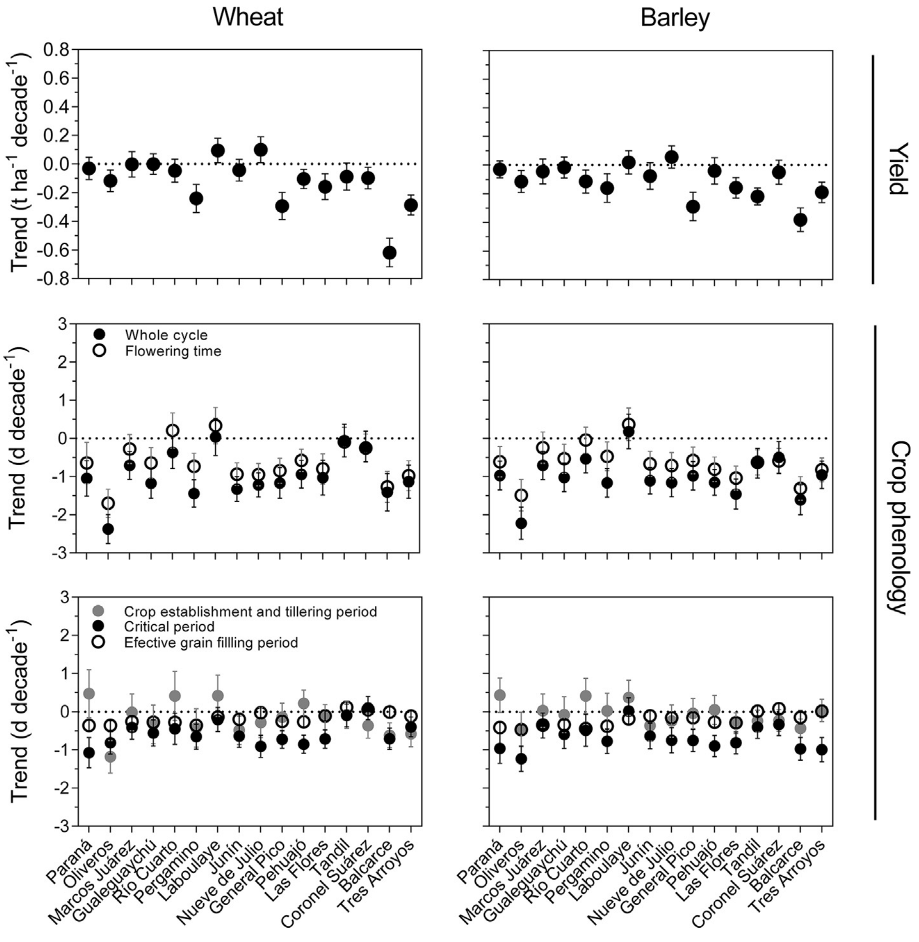

Fig. 3. Yield (upper panel) and phenology (middle and bottom panel) trends during 1961–2014 period in simulated wheat (left panel) and barley (right panel) crops using APSIM in optimal sowing dates (more details in Table 1) for sites in the Pampas, ordered from North (left) to South (right). Mean and standard error are indicated. The simulated crop cycle was divided into: (i) a crop establishment and tillering phase, from DC11 to the beginning of the critical period (i.e. 300 °C pre-anthesis), (ii) the critical period, and (iii) the effective grain filling period, from the end of critical period (i.e. 100 °C post-anthesis) to DC90.

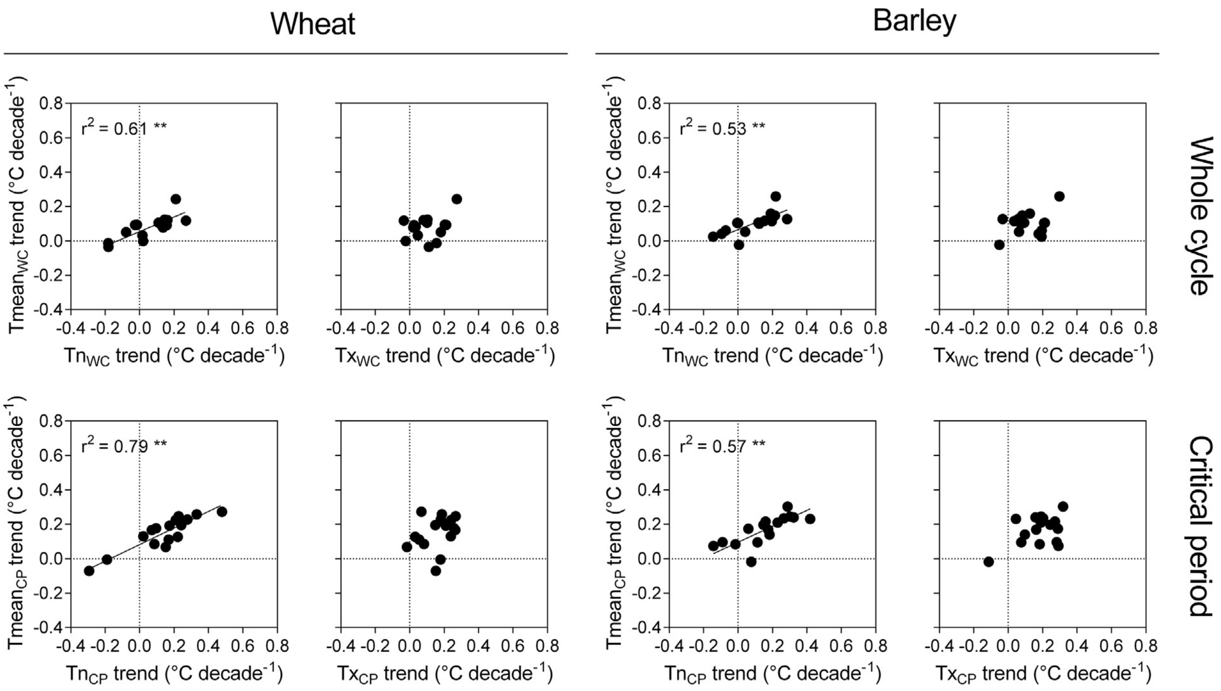

Fig. 4. Relationship between observed trends of average mean temperature (Tmean) and minimum (Tn) or maximum (Tx) temperatures for the whole crop cycle (WC, upper panel) or the critical period (CP, lower panel), in simulated wheat (left panel) or barley (right panel) crops using APSIM in optimal sowing dates (more details in Table 1) during 1961–2014 period for sites in the Pampas. Regression coefficient (model II) and the corresponding significant probability (**: $p < 0.01$, *: $p < 0.05$) are indicated.

than maximum temperatures, and associations between these temperature variations were not observed during the simulated whole crop cycle ($p = 0.54$ in wheat and $p = 0.07$ in barley) or the critical period ($p = 0.22$ in wheat and $p = 0.18$ in barley). Observed trends in average minimum temperature during the critical period were positively associated with changes observed during the crop establishment and tillering phase ($r = 0.80$, $p < 0.01$ for both wheat and barley) and the effective grain filling period ($r = 0.85$, $p < 0.01$ for wheat and $r = 0.78$, $p < 0.01$ for barley).

In the period studied, average minimum temperature during the critical period of both wheat and barley increased for most of the Pampas (Fig. 5), significantly in 6 and 7 sites in wheat and barley, respectively. In two southern sites a trend towards lower minimum temperature during the critical period was observed over time, significant only for simulated wheat in Coronel Suárez. On average, observed minimum temperature in the critical period increased 0.14 and 0.16 °C decade^{-1} in wheat and barley, respectively, during the 1961–2014 period.

3.2. *Yield and critical period duration response to minimum temperature variation during that crop phase*

Higher minimum temperatures observed during the critical period reduced simulated wheat and barley potential yield in the Pampas (Fig. 6). Wheat yield response to the minimum temperature increase was ca. −4% °C^{-1} on average for the whole region, ranging from −1% (not statistically significant) to −7% °C^{-1}. In absolute terms, these responses represented yield reductions of between 80 and 560 kg ha^{-1} °C^{-1} of warming, ca. 290 kg ha^{-1} on average for the whole region. Barley yield tended to be more sensitive to warming than wheat, ca. −5% °C^{-1} with a regional variation from −2% (not statistically significant) to −9% °C^{-1}. Barley yield was reduced ca. 340 kg ha^{-1} °C^{-1} on average in the whole region, ranging between 140 and 630 kg ha^{-1} °C^{-1} of minimum temperature increase during the

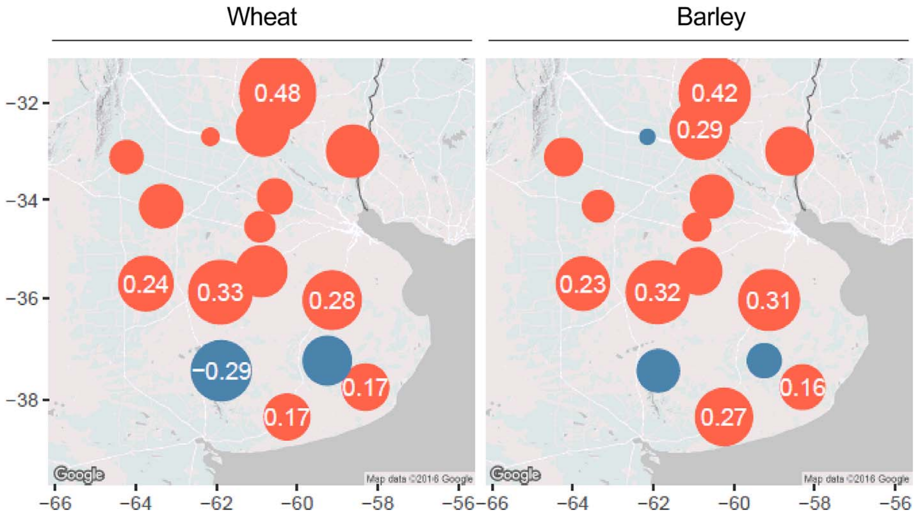

Fig. 5. Observed trends for average minimum temperature during the critical period, in simulated wheat (left) and barley (right) crops using APSIM in optimal sowing dates (more details in Table 1) during 1961–2014 period for sites in the Pampas. Circle size and colour correspond to change magnitude (°C decade^{-1}) and direction (red: increase, blue: decrease), respectively. Only statistically significant values ($p < 0.05$) are indicated. Longitude and latitude are indicated by y and x axes, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

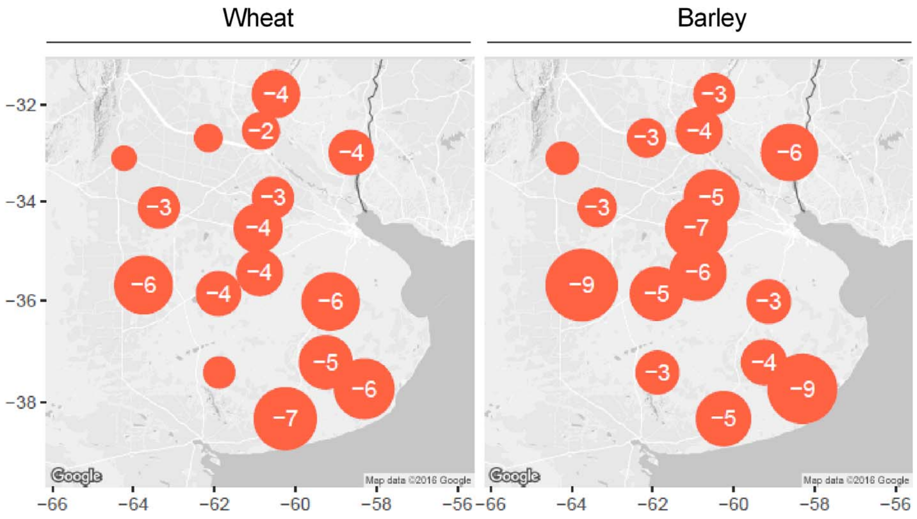

Fig. 6. Relative potential yield response (% °C^{-1}) to minimum temperature variations during the critical period, in simulated wheat (left) and barley (right) crops using APSIM in optimal sowing dates (more details in Table 1) during 1961–2014 period for sites in the Pampas. Circle size and colour correspond to response magnitude and direction (red: increase, in all cases), respectively. Only statistically significant values ($p < 0.05$) are indicated. Longitude and latitude are indicated by y and x axes, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

critical period.

Observed regional variability for yield response to minimum temperature increase was mainly explained by differences in the response of incident solar radiation accumulated during the critical period (Fig. 7). In both wheat and barley simulated crops, accumulated solar radiation response to minimum temperature had a similar range of variation to that observed in yield, but with higher sensitivity (i.e. greater reductions °C^{-1} were observed). On average across the Pampas, incident solar radiation accumulated during the critical period dropped ca. 8% and 9% °C^{-1} of minimum temperature increase during that phase in simulated wheat and barley crops, respectively. These results were mainly explained by the differences in average daily incident solar radiation during the critical period observed among sites (Table 2).

High minimum temperatures during the critical period reduced the relative duration of that crop phase similarly in simulated wheat and barley across the Pampas (inset Fig. 7 and Supplementary Fig. 3), ca. −6% °C^{-1} on average for the whole region, ranging from −4% to −8% °C^{-1}. In absolute terms, the critical period shortening under warming tended to be higher in barley than wheat, ca. 4 and 3 d °C^{-1}, respectively. Interestingly, large differences in yield response to warming were observed in sites where the critical period duration sensitivity was similar (inset Fig. 7). Regional variability in simulated yield response to warming could be also explained by differences in the response of average daily incident solar radiation during the critical period to minimum temperature ($r^2 = 0.57$, $p < 0.01$ for wheat and $r^2 = 0.64$, $p < 0.01$ for barley).

4. Discussion

4.1. Key phenological phases were shortened by warmer nights

Wheat and barley crops have been exposed to increasing night temperatures during recent decades in the Pampas. The asymmetric warming evidenced in previous studies in the region (Barros et al., 2015; Fernández-Long et al., 2013; Rusticucci, 2012), as in other important growing regions (e.g. India, Rao et al., 2015), was quantified in the present study from a crop perspective. Our climate analysis focused on the wheat and barley growing season in the Pampas and, using the simulated crop phenology, on crop stages relevant for yield determination. On average, the minimum temperature increase was higher than that of maximum temperature during the spring season (SON) in the 1961–2014 period, though variability was observed across the Pampas. Higher trends were located in northern sites, while in the South two sites situated inland (with less maritime influence) showed negative trends for minimum temperature. Evaluations of regional changes carried out with different agro-climate indexes (Fernández-Long et al., 2013), particularly frost occurrence (Fernández-Long et al., 2005), also found little or null temperature change during the las decades in these particular locations.

The asymmetric warming observed in the seasonal climate analysis was further dissected in the phenology driven analysis. The relevance of resource capture and utilization during the known critical period for wheat and barley yield determination (Arisnabarreta and Miralles,

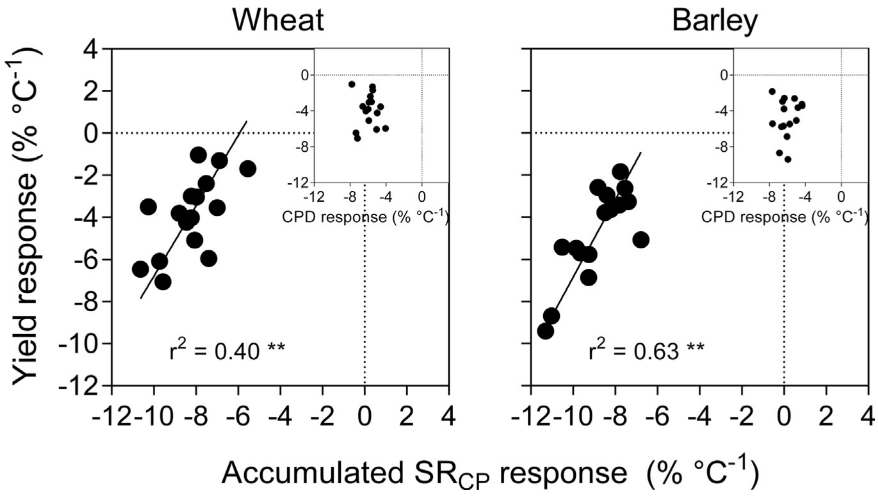

Fig. 7. Relationship between responses to minimum temperature variations during the critical period of relative both potential yield and incident solar radiation accumulated during the critical period in simulated wheat (left) or barley (right) crops using APSIM in optimal sowing dates (more details in Table 1) during 1961–2014 period for sites in the Pampas. Relationship between responses of relative yield and the critical period duration (CPD) is also included (inset). Regression coefficient (model II) and the corresponding significant probability (**: $p < 0.01$, *: $p < 0.05$) are indicated.

2008; Fischer, 1985; Fischer, 2008) was highlighted in the simulation study. Wheat and barley potential yield tended to decrease during the last five decades in most of the Pampas linked to crop cycle shortening under the observed asymmetric warming. Sadras and Monzon (2006) reported reductions of the simulated wheat cycle of up to 3 d decade^{-1}, in the Pampas and the Australian wheat-belt, mainly explained by early flowering. Our results were of similar magnitude, with wheat or barley presenting up to 2.5 d shorter cycle per decade (with a regional average of ca. 1 d decade^{-1}) associated with a shorter time to flowering. The critical period was the phase more sensitive to the asymmetric warming (regional minimum temperature trend of ca. 0.14 and 0.16 °C decade^{-1} in wheat and barley, respectively), shortened by 0.6 d decade^{-1} (up to 1.2 d decade^{-1}) vs. 0.1 and 0.2 d decade^{-1} during the vegetative and grain filling phases, respectively. Studies that analyze past and/or future trends in warm nights across different crop phases are scarce. Although warming during a certain phase could shift the development of the subsequent one to relatively cooler conditions, neutralizing the warming trend (Sadras and Monzon, 2006), in the present study, the observed minimum temperature trends observed in both the simulated wheat and barley critical period were positively associated with the trends observed in the other crop phases. Even though the crop cycle can be shortened under warm nights by accelerated development of all crop phases, most of yield reductions probably originated from the reduced resource capture during the critical period (García et al., 2015).

4.2. *Regional variation in the response of potential yield to warm nights is linked to lower radiation capture in the critical period*

Across the Pampas there were differences in thermal trends and simulated yield response to night warming, resulting in different outcomes for particular sites. For example, although in both Coronel Suárez and Balcarce (two southern sites) barley yield responded negatively to night warming, the negative trend observed in minimum temperature during the critical period and the lower yield sensitivity of the first site lead to negligible variations in simulated yield, while in Balcarce potential yield tended to decrease ca. 5% decade^{-1} during 1961–2014. On average for the whole region, simulated wheat and barley potential yield was significant reduced ca. 4% and 5% °C^{-1} of the observed minimum temperature increase during the critical period, respectively, during 1961–2014, varying between 2% and 9% °C^{-1}, in the range reported in the literature for different growing regions (chapter 10, Fischer et al., 2014). In Junín, a site at the same latitude than Buenos Aires, wheat and barley yield reductions were between 4% and 7% °C^{-1}. This simulated response is of similar magnitude to that obtained experimentally in a study specifically evaluating the impact of high night temperature in Buenos Aires (García et al., 2015). On the other hand, wheat yield reduction in Pergamino due to warming during the critical period (ca. 3% °C^{-1}), was lower than that reported by Magrin et al. (2009) (ca. 7% °C^{-1}), who showed a negative relationship between simulated potential yield and October–November minimum temperature during 1931–2000 period.

Which climate factors were behind the regional variability in yield response to temperature when the same cultivar is grown (simulated) in optimal sowing date without abiotic or biotic constraints? Sites with higher mean temperatures during the critical period could suffer greater yield losses due to warming (Gourdji et al., 2013; Ottman et al., 2012). In this study, the sowing date adjustment to avoid frost and heat at flowering, placed the critical period in similar temperature conditions (ca. 15 °C of mean temperature) across the Pampas. Incident daily solar radiation averaged during the critical period was different among sites. Higher solar radiation and, consequently, photothermal quotient values (Fischer, 1985; data not shown) were observed in the southern Pampas, explaining the higher yield potential of this zone (Magrin et al., 1993; Menéndez and Satorre, 2007). However, regional variability in incident solar radiation during the critical period did not explain by itself the differences in yield across the region. Instead, regional variability in the simulated yield response to the observed night warming was mainly explained by the response of incident solar radiation during the critical period to the minimum temperature increase. Solar radiation is steadily increasing with the day of the year, thus a shorter and earlier critical period due to night warming leads to lower average incident solar radiation during the phase (García et al., 2015). Therefore, the negative impact on yield was more important in sites where this reduction of resource availability was greater (e.g. in the South). A lower cumulative radiation during the critical period could result from (i) a shorter critical period, (ii) cloudy days, and/or (ii) the phase occurring during a time of the year with lower incident solar radiation and shorter days (towards winter). Asymmetric warming observed in different regions of the world is likely due to higher cloud cover (Dai et al., 1999; Lobell et al., 2007). In our study, incident solar radiation and minimum temperature averaged for the spring season (SON) were negatively associated in 10 out of 16 evaluated sites (r between -0.53 and -0.27, $p < 0.05$). In conclusion, wheat and barley crops were exposed to warmer night temperatures leading to an accelerated development that reduced the time of solar radiation capture and, in several sites, a lower solar radiation level that reduced even more the potential of the environment.

Crop yields were simulated under potential conditions (without water limitations) as soil water availability could mask the response of wheat and barley yield to night temperatures under rainfed conditions. Crop production can be divided in three levels: (i) the potential yield determined by growth-defining factors as the photothermal environment and cultivar physiological characteristics, (ii) the attainable yield modulated by growth-limiting factors as water and nutrients availability, and (iii) the actual yield affected by growth-reducing factors as biotic and abiotic stresses (Rabbinge, 1993; van Ittersum and Rabbinge, 1997). Our study focused on the first level, as the explored night temperature variations, which had a “non-stressful” thermal effect on yield through crop development, are a clear example of growth-defining factor of potential yield (Sadras and Dreccer, 2015). Growth-limiting factors, water mainly, have a quantitatively important impact on crop production in the Pampas (Aramburu Merlos et al., 2015; Satorre, 2011). Nevertheless, in the Pampas, there is marked inter-decadal variability in precipitation (Berbery and Barros, 2002), with a steady increase in annual precipitation (particularly in spring-summer) since the 1970s (Haylock et al., 2006; Rusticucci and Penalba, 2000), which can benefit wheat and barley production in zones strongly dependent of stored soil water as the Western Pampas (Asseng et al., 2012). We found a positive association between average minimum temperature and accumulated rainfall during the SON season (r between 0.28 and 0.68, $p < 0.05$) in the 1961–2014 period in 15 out of 16 evaluated sites. Considering these climate scenarios, higher attainable yields due to better water availability but with lower potential yields due to night temperature increase can be expected. This aspect, together with the likely complex interaction with water and nutrient availability and occurrence of stressful heat events, deserves further evaluation.

5. Conclusions

Our study showed significant potential yield losses in wheat and barley crops associated to warm nights in the Pampas, linked to lower cumulative radiation capture due to a shorter critical period and lower incident radiation. The obtained simulation results complement previous evidence from field experiments (García et al., 2015). Night warming is also likely to impact breeding progress. Genetic gains in Argentinean breeding programs since the 1960s range from ca. 0.53% (36 kg ha^{-1}) yr^{-1} in wheat (Lo Valvo et al., 2017) to ca. 0.72% (41 kg ha^{-1}) yr^{-1} in barley (Abeledo et al., 2003). Considering, on average for the whole region, the wheat and barley yield response to night warming during the critical period (ca. 4% and 5% °C^{-1}, respectively,) and the minimum temperature trend (ca. 0.14 and 0.16 °C decade^{-1} in wheat and barley, respectively), genetic gains could be ca. 11% higher if the observed asymmetric warming had not occurred. The length of the crop cycle and the timing of critical phases play a key role in the design of adaptation strategies to climate change (Fischer et al., 2014; Zheng et al., 2012), requiring combined breeding and management efforts. Given the regional variability, the variety by management package will need to be tailored for different sub-regions. Wheat and barley cultivars more tolerant to heat and frost events will add flexibility to the sowing date calendar, adding to the cycle length variation regulated by flowering genes available in the commercial cultivars. Cultivars that can regulate their development in response to the rate to night warming would provide a clear advantage (García et al., 2016).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2017.12.009.

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