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Associations between climate variables and beef cow fertility following fixed-time artificial insemination during an 11-years period in the central region of Chile

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Research Article

Keywords: Beef cows, climate variables, fixed-time artificial insemination, 11-years period

Posted Date: October 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11296584/v1

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Additional Declarations: No competing interests reported.

Abstract

Global average surface temperature is expected to rise throughout this century affecting key aspects of livestock productivity, including animal health and reproduction. The frequency of extremely hot days during summer in Chile and South America is expected to double over the next years resulting in environmental conditions that may affect beef cattle. The objective of the present study was to analyze the impact of climatic variables, including temperature, rainfall, relative humidity and solar radiation on pregnancy rates of crossbred beef cows in central Chile over a period of 11 years following an estradiol-based fixed time artificial insemination (FTAI) program. Climate data and records from 1,011 beef crossbreed cows belonging to 15 small holders from the central region of Chile included in a FTAI program were analyzed during an 11-year period. Although climate conditions evidenced an intense drought and raising air temperature, probability of pregnancy of cows were not significantly different during this period. Cows with calving to pregnancy interval (CPI) > 75 days had 78% higher probability of pregnancy in comparison with CPI < 60 days. Moreover, cows in intervals of body condition score (BCS) 2.76-3.00 and 3.01-4.00 had significantly higher PR (PR = 57.5 and 62.3, OR = 1.86 and 3.52, respectively) compared to cows with BCS < 2.76. In conclusion, beef cows following a FTAI program in the central region of Chile included in this study did not show significant reduction in reproductive performance between years 2014 and 2024. However, cows with lower BCS (< 2.75) and lower CPI (< 60 days) had fewer probability of pregnancy.

Introduction

Although projections of climate change vary throughout this century, global average surface temperature is expected to rise by approximately 0.3°C to 4.8°C by the year 2100 (Stocker et al., 2013; Zhao et al., 2024). This rise in temperature could significantly impact livestock production by altering yield and nutritional quality of feed crops and forage (Chapman et al., 2012), reducing water availability, affecting animal growth and milk output (Henry et al., 2012; Silveira et al., 2026), and influencing the prevalence of diseases and reproductive performance (Silveira et al., 2026; Nardone et al., 2010). These effects are largely driven by rising temperatures, elevated atmospheric CO_2 levels, changes in precipitation patterns, or a combination of these factors (Zhao et al., 2024; Henry et al., 2012; Nardone et al., 2010; Aydinalp and Cresser, 2008; IFAD, 2010; Polley et al., 2013; Reynolds et al., 2010; Thornton et al., 2009). Temperature plays a critical role in determining key aspects of livestock productivity, such as water supply, animal health, reproduction, and overall performance. Forage quantity and quality are influenced by the interplay of rising temperatures, increased CO_2, and variable precipitation, while livestock diseases are predominantly affected by temperature increases and fluctuations in rainfall.

Several regions worldwide have experienced shifts in climate patterns, including rising average temperatures and changes in rainfall distribution, leading to hotter summers and prolonged droughts (Meehl et al., 2007; Eslamizad et al., 2020). In Chile, climate projections have indicated that minimum and maximum temperatures will rise by more than 2°C and 6°C, respectively, across all seasons throughout the entire territory (Araya-Osses et al., 2020). Similarly, the frequency of extremely hot days

during the December–January–February period in South America is reported to double for the next years (Feron et al., 2019). Prior to 2010, the risk of heat stress for cattle in Chile was largely confined to the central region (Arias and Mader, 2010); however, since then, the occurrence of heatwaves has increased significantly, affecting also the southern regions (DMC, n.d.-a).

Under extensive grass-fed systems, beef cattle spend most of the year outdoors, resulting in continuous exposure to environmental conditions and an increased susceptibility to chronic climate-related stress. Among these stressors, heat stress has been the most widely investigated and is commonly defined using the temperature–humidity index (THI). During extreme conditions, THI values can consistently exceed the animals thermoneutral zone, thereby compromising performance. Evidence suggests that THI values above 75 negatively affect cows, while bulls exhibit adverse effects at values exceeding 72, both thresholds indicating heat stress in beef cattle (St-Pierre et al., 2003). However, THI may underestimate the actual magnitude of climatic stress, as it does not incorporate key environmental factors such as solar radiation and wind speed. It is now broadly recognized that ambient temperature, relative humidity, solar radiation, and wind speed that collectively determine thermal balance in cattle (Hahn et al., 2009; Mader et al., 2010; Gaughan and Mader, 2014; Lees et al., 2019). To overcome this limitation, modified indices have been developed that integrate these additional variables (Mader et al., 2006), leading to the formulation of the Comprehensive Climate Index (CCI), which accounts for all four parameters (Mader et al., 2010). In this regard, studies conducted in Chile have shown that solar radiation is a major contributor to the daily heat load experienced by cattle (Arias et al., 2021), particularly in grazing systems with limited shade availability, as commonly observed in the central and southern regions. Despite these advances, long-term evaluations of the effects of climatic variables on fertility in beef cows—especially in the context of fixed-time artificial insemination (FTAI) remain lacking in Chile.

The impact of climate on livestock physiology varies in magnitude and is influenced by a range of factors. These include abiotic elements such as temperature and humidity, as well as biotic factors including genetic potential, age or developmental stage, and nutritional status (Rojas-Downing et al., 2017). Heat stress negatively affects reproductive performance through multiple cellular mechanisms, physiological processes, and developmental stages. These include the pubertal development, activity of the hypothalamic-hypophyseal-ovarian axis, gamete quality, estrus expression, prepartum period, conception and embryonic development (Ahmed et al., 2021; Roth, 2020). The biological mechanisms underlying these effects are complex and continue to be investigated. Among the most studied reproductive processes impacted by heat stress are the function of the hypothalamic-pituitary-ovarian axis, secretion of gonadotropins, follicular development, steroidogenesis (Roth, 2020), and corpus luteum function (Tariq et al., 2025). In beef cattle, heat stress has been associated with a reduction in corpus luteum weight (Biggers et al., 1987) and diameter (Burke et al., 2001). Additionally, heat stress leads to decreased levels of key reproductive hormones such as progesterone, prolactin, and estradiol, resulting in reduced conception rates and increased pregnancy loss (Burke et al., 2001; Kadokawa et al., 2012). In addition, heat stress alters the expression of genes related to milk production in beef cattle, reducing the total production of milk and the protein content of the milk (Eitam et al., 2009). Several

animal-based indicators of behavior may be used to detected heat stress such as longer time spent standing, time spent looking for shaded areas, increased water consumption, changes in feeding and tendency to graze when temperatures are cooler (Lees et al., 2019). Also, classic physiological indicators of heat stress include increased sweating, faster respiration (breaths per minute), higher panting score and higher body temperature (Lees et al., 2019).

Despite the benefits of FTAI programs that include genetic improvement and dispense of estrus detection, incorporation of these protocols in beef cattle worldwide has been slow. Considering climate change during the last decades and increasing environmental temperatures that reduce intensity of estrus, incorporation on FTAI programs in cattle managed under extreme climate conditions may have beneficial effect. Hence, the objective of the present study was to analyze the impact of climatic variables, including temperature, rainfall, relative humidity and solar radiation on fertility of crossbred beef cows in central Chile over a period of 12 years following an estradiol-based FTAI program.

Materials and Methods

Farm locations

Beef herds recorded in this study belonged to 15 small holders of beef cattle that were located in the area of San Pedro de Melipilla in the Province of Melipilla, Central Region of Chile (-33.9191515 latitude, -71.5098759 longitude). This area of the dry interior of the region has a semi-arid mediterranean climate and an elevation above sea level of ~ 122 mts. The study was conducted over the course of 12 breeding seasons between 2014 and 2025. Breeding seasons corresponded to the month of September to November.

Climate variables

Daily maximum and minimum temperatures and rainfall for San Pedro de Melipilla (-33.9191515 latitude, -71.5098759 longitude) were obtained from WorldClim database (Fick and Hijmans, 2017) using the QGIS software (QGIS Development Team). Hourly records of air temperature (AT, ºC), relative humidity (RH, %), wind speed (WS, m/s), and solar radiation (SR, W/m2) were obtained for the period 2014 to 2025 from MeteoChile (DMC). With this information, three thermal comfort indices were estimated: (1) the temperature-humidity index; THI1 = (0.8 × AT) + ((RH/100) × (AT– 14.4) + 46.4 (Hahn et al., 2009), (2) THI2 adjusted for solar radiation and wind speed; THIa = THI + 4.51– (1.992 × WS) + (0.0068 × SR) (Mader et al., 2006), and (3) CCI = T + RHC + WSC + RADC (Mader et al., 2010), where:

$RHC = e^{(0.00182\times RH+1.8\times10-5\times T\times RH)} \times (0.000054\times T2 + 0.00192\times T - 0.0246) \times (RH - 30)$

$WSC=[-6.56/e\{1/(2.26\times WS + 0.23)0.45\times(2.9 + 1.14\times10 - 6\times WS2.5 - \log0.3(2.26\times WS + 0.33) - 2\}] - 0.00566\times WS2 + 3.$

$$RADC = 0.0076\times RAD - 0.00002\times RAD\times T + 0.00005\times T2\times \sqrt{RAD} + 0.1\times T - 2$$

Herds and animals

The study included 1,011 beef crossbreed cows including Overo Colorado, Hereford and Angus. Animals were fed natural pasture without fertilization with an average annual production between 1200–1600 kg MS/hectare/year. The months of greatest supply of phytomass occur in August to October and the period without rains includes from November to April (Roldán-Ruiz et al., 1996). During the period of food shortages, animals were supplemented with hay from oats and wheat.

The health status of the herd was evaluated by a veterinarian and consists mainly of vaccination and antiparasitic treatments twice a year. At the time of starting the FTAI protocol (day 0) the variables age (1–10 years), parity (1–6 parturitions), and date of last calving (> 30 days) were recorded for each cow. These data was obtained from the records of each producer. At the time of performing the AI (day 10) the calving-to-pregnancy interval (CPI) of the cow was determined. Body condition score (BCS, 1–5) was assessed (Mulliniks et al., 2012) by visual inspection and palpation. The convexity of body curves, prominence of the hip bones, ribs, transverse and spinous processes of lumbar vertebrae, and fatty deposits at the base of the tail were visualized. By palpation, the area under the transverse processes was pressed to correlate it with the force necessary to feel this edge and thus determine the amount of fat coverage.

Fixed-time estrus synchronization protocol

On day 0, a pregnancy diagnosis was made to discard pregnant cows and to initiate estrus synchronization only in non-pregnant cows. Cows included in the estrus synchronization protocol were administered 2 mg of estradiol benzoate (Syntex, Buenos Aires, Argentina) i.m. plus the insertion of an intravaginal controlled release device containing 0.5 g of progesterone (Bovine Intravaginal Device, Syntex, Buenos Aires, Argentina). On day 8, the intravaginal device was removed and 1 mg of estradiol cypionate (E.C.P., Pfizer, Sao Paulo, Brazil) and 500 μg of cloprostenol sodium (Ciclase, Syntex, Buenos Aires, Argentina) were administered i.m. Cows were subjected to FTAI between 52 and 56 hours after the intravaginal progesterone device was removed.

Pregnancy diagnosis

For the diagnosis of pregnancy, an ultrasound scanner (Esaote Piemedical model Tringa Linear, Netherlands) with a 7 MHz transducer was used. Pregnancy diagnosis was performed on day 50 post IA to differentiate cows pregnant from AI (50 days of gestation, with a fetus of approximately 5 cm) from those pregnant from a cleanup bull (29 days of gestation, with a fetus of approximately 1 cm). Those cows in which a fetus with the presence of a heartbeat were selected as pregnant.

Data analysis

Pregnancy rates (PR) were calculated as the number of cows confirmed pregnant by ultrasound at 50 days post-AI divided by the total number of cows artificially inseminated during the breeding season (90 days). PR were calculated according to different categories of year (2014–2025), BCS (2.00-2.75; 2.76-3.00; and 3.01-4.00), CPI (30–59; 60–75; and > 75), parity (1–2; 3–4; and 5–6), and age of the cow (1–3; 4–6; and 7–10). The probability of pregnancy occurrence (Odd Ratio, OR) was calculated using a logistic regression model (InfoStat software, Córdoba, Argentina). The independent variables included in the model were: year, BCS, CPI, parity and age. Subsequently a second logistic regression model was analyzed for the probability of pregnancy occurrence (Odds Ratio) using THI1 and THI2 as independent variables. For all statistical analyses, a significance value of $P < 0.05$ and a CI = 95% were used.

Results

Climate variables in the central region of Chile during 2000–2025 period

Climate variables obtained from the 2000–2025 including rainfall, maximum and minimum temperature were analyzed to have a wider perspective of the climate variation during a 25-year interval in the zone. Yearly accumulated rainfall achieved highest values in 2002 with 792.33 mm and lowest values in 2019 with 162 mm (Fig. 1). Thereafter, values of rainfall increased to 534.2 mm in 2024. Maximum temperatures have ranged from averages values of 19.73 to 21.71°C in years 2000 and 2017, respectively. Average maximum temperature for 2024 was 20.83°C. Average minimum temperature ranged from 9.01°C (2002) to 11.22°C (2016) with values of 10.75°C during 2024.

Daily climate variables including air temperature, relative humidity, solar radiation and wind intensity were collected for the 2014–2025 period. Air temperature ranged yearly from 13.4 (2014) to 14°C (2023) and monthly from 8.28 (July) to 18.8°C (January) (Fig. 2A,C). Highest and lowest yearly relative humidity values were 77.2% (2016) and 69.88% (2019). Monthly, highest and lowest relative humidity values were 85.95% (July) and 63.91% (December). Solar radiation values ranged yearly from 772 to 837.33 watt/m2 (2021) and monthly from 488.17 (June) to 1078.72 (December) (Fig. 1B,D). Wind intensity values ranged yearly from 1.18 (2015) to 0.76 (2024) and monthly from 0.59 (May) to 1.43 (January). Accordingly, THI1 values ranged from 56.07 to 57.73 in years 2022 and 2023, respectively (Fig. 2A). This index showed greater year-to-year variation with the highest values in January (63.52) and lowest value in July (47.79) (Fig. 2C). In comparison, TH2 values ranged from 63.96 to 65.2 in 2014 and 2023, respectively. Moreover, variation of TH2 across months ranged from 74.56 to 54.42 for February and July, respectively. Analysis of annual temperatures during breeding seasons (September to November) indicated that the highest values were observed in 2016 (14.2) and 2019 (14.6) and lowest values on 2017 (13.1) and 2023 (13.1) (Fig. 2E). Relative humidity values were highest on in 2015 (77.2) and lowest in 2019 (63.1). THI1 and TH2 values ranged from 55,9 (2015) to 58 (2019) and from 64.6 (2017) to 66.6 (2019), respectively.

Yearly solar radiation ranged from 994.2 (2015) to 899.7 (2018). The highest and lowest wind intensity values were detected in 2016 (1.27) and (2024) 0.87, respectively (Fig. 2F).

Pearson correlations between monthly values of THI1 and THI2 (0.99), THI1 and CCI (0.97), and THI2 and CCI (0.98) were significant (Fig. 3). Significant correlation between yearly THI1 and THI2 (0.94) was also detected; however, correlations between yearly THI1 and CCI (-031) and between THI2 and CCI (0.0225) were not significant.

Effects of yearly breeding season and reproductive variables on pregnancy rates (PR) of beef cows followed FTAI during 11-year period

Logistic regression was performed to estimate odds ratios for PR according to years, BCS, CPI, parity and age of cows (Table 1). Odd ratios for PR were not significant across years of breeding seasons (2014–2024). In comparison, cows with BCS between 2.76-3.00 and 3.01-4.00 had PR of 57.5 and 62.3, with OR = 1.86 (P = 0.03) and 3.52 (P = 0.04), respectively. Moreover, cows with CPI between 60–75 and > 75 had PR of 60.3 and 57.9 with OR = 1.41 (P = 0.02) and 1.78 (P = 0.04), respectively. PR of cows at different parity and age intervals were not different (P > 0.05).

Table 1
Logistic binomial regression for the effects of yearly breeding season and reproductive variables on pregnancy rates (PR) of beef cows.

Variable	AI (no.)	PR (%)	Odd Ratio	95% Confidence Interval	P value
Year					
2014	84	63	1	-	-
2015	93	48	0.84	0.52, 10.42	0.98
2016	98	70	1.2	0.49, 12.50	0.55
2017	94	40	0.45	0.37, 14.49	0.14
2018	88	61	1.1	0.14, 12.20	0.45
2019	94	50	0.94	0.38, 9.10	0.34
2020	82	51	0.98	0.19, 9.17	0.56
2021	93	43	0.75	0.52, 10.42	0.15
2022	95	51	0.89	0.67, 8.67	0.34
2023	92	52	0.77	0.54, 7.35	0.45
2024	98	56	0.79	0.65, 6.56	0.32
BCS					
2.00-2.75	234	42.1	1	-	
2.76-3.00	445	57.5	1.86	1.81–4.3	0.03
3.01-4.00	332	62.3	3.52	1.3–9.54	0.04
CPI					
30–59	278	49	1	-	
60–75	388	60.3	1.41	0.55–3.61	0.02
> 75	345	57.9	1.78	0.75–4.23	0.04
Parity					

[a]Odds ratio is the estimated odds of becoming pregnant for a cow AI in a particular category relative to the baseline category for that variable for the effects of the other explanatory variables shown. Odds ratio = 1: no effect of pregnancy; >1: increased probability of pregnancy; <1: decreased probability of pregnancy compared with the baseline category.

[b]When CI encompasses 1, the odds ratio is not significant.

[c]Value significantly different from baseline category ($P < 0.05$).

Variable	AI (no.)	PR (%)	Odd Ratio	95% Confidence Interval	P value
Year					
1–2	274	57	1	-	
3–4	392	48	1.22	0.84–4.56	0.56
5–6	345	34	1.13	0.78–5.67	0.89
Age					
1–3	285	45	1	-	
4–6	372	55	1.72	0.71–4.17	0.23
7–10	354	63	1.49	0.89–6.09	0.08
[a]Odds ratio is the estimated odds of becoming pregnant for a cow AI in a particular category relative to the baseline category for that variable for the effects of the other explanatory variables shown. Odds ratio = 1: no effect of pregnancy; >1: increased probability of pregnancy; <1: decreased probability of pregnancy compared with the baseline category.					
[b]When CI encompasses 1, the odds ratio is not significant.					
[c]Value significantly different from baseline category ($P < 0.05$).					

Effects of temperature-humidity index 1 and 2 during breeding season on pregnancy rate (PR) of beef cows

Logistic regression analyses were also conducted to estimate OR for PR among THI1 and THI2 intervals during breeding seasons (Table 2). PR and OR of cows AI at different THI1 intervals (51–54; 54–57; 57–61) were not different ($P > 0.05$). Moreover, cows AI at THI2 between 60–64; 64–67 or 67–71 were not significantly different.

Table 2
Logistic binomial regression for the effects of temperature-humidity index 1 and 2 during breeding season on pregnancy rate (PR) of beef cows.

Variable	AI (no.)	PR (%)	Odd Ratio	95% Confidence Interval	P value
THI1 (BS)					
51–54	345	54.8	1	0.36, 8.10	0.45
54–57	316	53.4	1.15	0.2, 6.17	0.12
57–61	350	55.2	1.33	0.42, 11.42	0.10
THI2 (BS)					
60–64	344	55.6	1	0.57, 8.68	0.34
64–67	322	56.2	1.09	0.53, 7.25	0.34
67–71	345	53.4	1.12	0.63, 5.56	0.33

[a]Odds ratio is the estimated odds of becoming pregnant for a cow AI in a particular category relative to the baseline category for that variable for the effects of the other explanatory variables shown. Odds ratio = 1: no effect of pregnancy; >1: increased probability of pregnancy; <1: decreased probability of pregnancy compared with the baseline category.

[b]When CI encompasses 1, the odds ratio is not significant.

[c]Value significantly different from baseline category ($P < 0.05$).

Discussion

The impacts of climatic variables including rainfall, air temperature, relative humidity, solar radiation and wind speed were analyzed on fertility parameters of crossbred beef cows in central Chile over an 11-year period following a FTAI program. Yearly rainfall values in this area have evidenced a reduction of ~ 80% since 2002, achieving lowest values in 2019 and 2021. Thereafter, yearly accumulated precipitations have increased, achieving 534.2 mm in 2024. Despite western South America and central Chile exhibiting highly variable climate due to Mediterranean-like conditions, since 2010 the region has undergone an uninterrupted dry spell, with exceptionally arid conditions in 2019 and 2021 (Garreaud et al., 2025). The pronounced reduction in winter precipitation during these years has triggered severe environmental effects including intense degradation of plant species and natural forests, accompanied by a decline in grassland productivity (Miranda et al., 2023; Arroyo et al., 2020). These conditions have limited the availability of forages and increased the price of feed, raising important concerns among producers and especially small holders regarding cattle growth, welfare and reproduction.

Although climate conditions during the 11-year interval evidenced an intense drought and increasing air temperature, probability of pregnancy of cattle followed FTAI were not significantly different during this period. Moreover, THI1 and THI2 values were not higher than 61 and 71 during breeding seasons, which

indicate that cattle was not exposed to severe heat stress. Yearly air temperatures increased by 0.6°C between 2014 and 2023 and fluctuated by 10.5°C between July to January. Yearly relative humidity values decreased in 7.3% between 2016 and 2019, where highest and lowest relative humidity values were recorded in July (85.95%) and December (63.91%), respectively. Accordingly, THI1 values ranged from 56.07 to 57.73 in years 2022 and 2023 with highest monthly values in January (63.52) and lowest value in July (47.79). It has been reported that THI1 values between 70 and 74 may result in heat stress and potential negative effects in livestock (LCI, 1970). THI values ≤ 74 are classified as alert, 74 < THI < 79 as danger, and 79 ≤ THI < 84 as emergency in cows. In bulls, negative effect has been reported at THI > 72 (St-Pierre et al., 2003). THI1 values of < 70 indicate that cattle in the central area of Chile were not raised under heat stress conditions; however, mean values of temperature and humidity may underestimate the occurrence of heatwaves where temperature may exceed 35°C-37°C (SENAPRED, 2026). Moreover, THI1 may underestimate climatic stress in beef cattle since it does not consider exposure to radiation or wind velocity. THI2 values ranged from 63.96 to 65.2 for years 2014 and 2023, respectively. Moreover, variation of THI2 among months was 74.56 to 54.42 for February and July, respectively. Studies conducted in New Zealand, with weather conditions comparable to those of Southern Chile, have demonstrated that body temperature of dairy cows is affected by air temperature and solar radiation (Kendall et al., 2006). In Nebraska, USA, (Amundson et al., 2006) has been found a decrease in conception rates at THI greater than 72.9, but at the same time reported a positive effect of wind speed on conception rate. Similar responses were reported in Australia (Morton et al., 2007). Previous research conducted in Chile has shown that solar radiation contributes to the daily heat load of animals, especially those under grazing production systems and limited access to shade (Arias et al., 2021). However, beef producers during summer heat adopt mitigation strategies include maintaining shading areas of forest, continuing provision of drinking water, feeding during late afternoon/evening, and controlling of flies to prevent energy expenditure from swatting and congregation. Additional mitigation strategies including provision of artificial shading structures, ventilation or sprinklers are not commonly used.

FTAI programs are not commonly used among small holders of beef cattle in Chile. This may be related to the costs of hormones, doses of semen, AI materials, and the lack of technical knowledge and the reduced appreciation of the economic benefits of AI programs. In the context of climate change conditions, FTAI programs can bring important benefits for reproductive management of the cows by avoiding estrus detection. Extreme heat conditions has been linked to changes in estrus behavior of beef cattle, consequence of fewer mounts per cycle in the summer and longer interval between mounts (Provolo and Riva, 2009). Heat stress during the week before insemination and at the insemination day limits estrus signs (Provolo and Riva, 2009), implying failure in estrus detection and suboptimal insemination timing. Consequently, an increase of silent ovulations in periods of heat stress has been reported (Kadokawa et al., 2012). Reduction in the expression of estrus behavior may be associated with physical lethargy caused by heat stress (Hansen and Arechiga, 1999) but has also been associated with increased cortisol secretion (Elvinger et al., 1992) and reduction in peripheral concentrations of estradiol-17β (Roth, 2020). In this context, the use of FTAI reduce errors associated with low intensity estrus,

timing of AI, and costs of transportation of AI technician, which consequently increase the number of cows inseminated.

In the present study, cows with less than 60 days post-partum had lower PR compared to cows over 60 days postpartum (49 versus 60.3%). Moreover, cows with > 75 days postpartum had 78% higher probability of pregnancy in comparison with < 60 days postpartum. These results indicate that OR for pregnancy increase with days postpartum, which is consistent with previous studies (Ball and Peters, 2004). Main physiological events occurring during the post-calving period include uterine involution and onset of ovarian cyclicity leading to restoration of cow reproductive capacity. Beef cows, with BCS > 2.5 (scale 1 to 5), with lactating calf and adequate postpartum nutritional management are usually inseminated > 60 days postpartum (Ball and Peters, 2004). However, the use of progestogens in FTAI may improve reproductive response in cows and reduce days to first insemination to 45 days postpartum (Bó and Baruselli, 2014).

BCS is an important variable associated with productive and reproductive efficiency of cows (Ball and Peters, 2004; Mulliniks et al., 2012). Voluntary feed intake begins to decline when ambient temperatures reach approximately 25–27°C (Beede and Collier, 1986). However, the temperature threshold for reductions in dry matter intake (DMI) is modulated by diet composition, with high-roughage diets eliciting earlier and more pronounced decreases in DMI than diets containing lower roughage levels (Beede and Collier, 1986). Cows under heat stress in grazing conditions by removing access to artificial of shade from prepartum until 50 ± 4 d postpartum have shown to decreased plasma concentrations of IGF-1 and BCS during late gestation (Izquierdo et al., 2023). Post-calving, the time it takes for cows to regain their reproductive functionality is closely related to their BCS and directly influences the productive goal of generating one calving per year (Ball and Peters, 2004). It has been reported that animals with BCS above 2.5 points (scale 1–5) have uterine involution and restoration of cyclicity at 30 and 55 days respectively (Dalton et al., 2012). Conversely, the number of days that cows need to recover their reproductive functionality can be increased in cows with BCS < 2.5 points (Mulliniks et al., 2012; Dalton et al., 2012; Montiel and Ahuja, 2005). Body condition at the beginning of the breeding season is one of the most important variable that influences PR and it is recommended that cows eligible for FTAI protocols should display BCS > 2.25 points on a scale of 1 to 5 (Mulliniks et al., 2012; Ball and Peters, 2004; Renquist et al., 2006). In agreement with this data, in the present study, cows in intervals of BCS 2.76-3.00 and 3.01-4.00 had significantly higher PR (PR = 57.5 and 62.3, OR = 1.86 and 3.52, respectively) compared to cows with BCS < 2.76. Cows with greater BCS (≥ 5 vs. < 5; scale 1–9) at beginning of breeding season had greater pregnancy and calving rate, calving earlier and weaning heavier calves (Cooke et al., 2021). Also, BCS affects the physiology, and cows with greater BCS have greater blood concentrations of insulin-like growth factor 1 (IGF-1), leptin, insulin, thyroxine, glucose and non-esterified fat acids (NEFA) (Ciccioli et al., 2003). Further, BCS also affects the ovary functions, and cows with greater BCS have greater dominant follicle size, corpus luteum area, estrus rate and ovulation rate (Nishimura et al., 2018). Thus, cows with greater BCS at beginning of FTAI protocol or that gained or maintained BCS during synchronization and after AI had greater ovarian structures development, estrus expression, pregnancy rate and embryo size.

Conclusions

In conclusion, in spite reduction in ~ 80% in rainfall since 2002 and increase in air temperature in 0.6°C between 2014 and 2023, beef cows following a FTAI program in the central region of Chile included in this study did not experience significant reduction in reproductive performance between years 2014 and 2025. PR were not affected by yearly breeding season; however, cows with lower BCS (< 2.75) and lower CPI (< 60 days) had fewer probability of pregnancy. Strategies adopted by small holders of beef cattle including providing supplementary crops and climate mitigation strategies may have protected cow reproductive performance from climate conditions.

Declarations

Ethics approval

All experimental procedures were approved and performed in accordance with the guidelines and regulations of the Bioethics Committee of the Pontificia Universidad Católica de Chile (Certificate No. 260715001).

Consent to participate

Not applicable

Consent to Publish

Not applicable

Declaration of competing interest

None of the authors has any conflict of interest to declare.

Declaration of generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used ChatGPT in order to improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Funding

This study was supported by cattle genetic improvement program, Institute for Agricultural Development (INDAP) from the Ministry of Agriculture, Government of Chile.

Author Contribution

Conceptualization, C.D. and O.A.P.; Methodology, C.D., B.L., B.Q., and O.A.P.; Software, O.A.P, Validation, C.D., F.J.M., L.P. and O.A.P.; Formal Analysis, C.D., V.H.P, M.D.R., F.J.M., L.P., M.D. and O.A.P; Investigation, C.D., V.H.P, M.D.R., F.J.M., L.P., M.D. and O.A.P; Resources, C.D. and O.A.P.; Data Curation, C.D. and O.A.P.; Writing— Original Draft Preparation, C.D. and O.A.P.; Writing—Review and Editing, F.J.M., L.P. and O.A.P; Visualization, C.D., F.J.M., L.P. and O.A.P; Supervision, C.D., B.L. B.Q. and O.A.P.; Project Administration, B.L. and O.A.P.; Funding Acquisition, C.D. and O.A.P. All authors have read and agreed to the published version of the manuscript.

Data Availability

Climate data was obtained from the following sources:1) QGIS Development Team (n.d.) QGIS geographic information system. https://www.qgis.org/. Accessed 1 July 20262) Dirección Meteorológica de Chile (DME) (n.d.) https://www.meteochile.gob.cl/PortalDMC-web/index.xhtml. Accessed 1 July 2026

References

1. Ahmed BMS, Younas U, Asar TO, Monteiro APA, Hayen MJ, Tao S, Dahl GE (2021) Maternal heat stress reduces body and organ growth in calves: relationship to immune status. JDS Commun 2:295–299. https://doi.org/10.3168/jdsc.2021-0098
2. Amundson JL, Mader TL, Rasby RJ, Hu QS (2006) Environmental effects on pregnancy rate in beef cattle. J Anim Sci 84:3415–3420. https://doi.org/10.2527/jas.2005-611
3. Araya-Osses D, Casanueva A, Román-Figueroa C, Uribe JM, Paneque M (2020) Climate change projections of temperature and precipitation in Chile based on statistical downscaling. Clim Dyn 54:4309–4330. https://doi.org/10.1007/s00382-020-05231-4
4. Arias RA, Mader TL (2010) Determination of potential risk of heat stress of cattle in four locations of central and southern Chile. Arch Med Vet 42:33–39. https://doi.org/10.4067/S0301-732X2010000100005
5. Arias RA, Delgado C, Keim JP, Gandarillas M (2021) Use of the comprehensive climate index to estimate heat stress response of grazing dairy cows in a temperate climate region. J Dairy Res 88:154–161. https://doi.org/10.1017/S0022029921000406
6. Arroyo MTK, Robles V, Tamburrino I, Martínez-Harms J, Garreaud RD, Jara-Arancio P, Pliscoff P, Copier A, Arenas J, Keymer J, Castro K (2020) Extreme drought affects visitation and seed set in a plant species in the central Chilean Andes heavily dependent on hummingbird pollination. Plants 9:1553. https://doi.org/10.3390/plants9111553
7. Aydinalp C, Cresser MS (2008) The effects of climate change on agriculture. World Acad Sci Eng Technol 5:672–676
8. Ball PJH, Peters AR (2004) Reproduction in cattle, 3rd edn. Blackwell Publishing, Oxford. https://doi.org/10.1002/9780470751091

9. Beede DK, Collier RJ (1986) Potential nutritional strategies for intensively managed cattle during thermal stress. J Anim Sci 62:543–554. https://doi.org/10.2527/jas1986.622543x
10. Biggers BG, Geisert RD, Wettemann RP, Buchanan DS (1987) Effect of heat stress on early embryonic development in the beef cow. J Anim Sci 64:1512–1518. https://doi.org/10.2527/jas1987.6451512x
11. Bó GA, Baruselli PS (2014) Synchronization of ovulation and fixed-time artificial insemination in beef cattle. Animal 8(Suppl 1):144–150. https://doi.org/10.1017/S1751731114000822
12. Burke JM, Spiers DE, Kojima FN, Perry GA, Salfen BE, Wood SL, Patterson DJ, Smith MF, Lucy MC, Jackson WG, Piper EL (2001) Interaction of endophyte-infected fescue and heat stress on ovarian function in the beef heifer. Biol Reprod 65:260–268. https://doi.org/10.1095/biolreprod65.1.260
13. Chapman S, Chakraborty S, Dreccer M, Howden S (2012) Plant adaptation to climate change: opportunities and priorities in breeding. Crop Pasture Sci 63:251–268. https://doi.org/10.1071/CP11303
14. Ciccioli NH, Wettemann RP, Spicer LJ, Lents CA, White FJ, Keisler DH (2003) Influence of body condition at calving and postpartum nutrition on endocrine function and reproductive performance of primiparous beef cows. J Anim Sci 81:3107–3120. https://doi.org/10.2527/2003.81123107x
15. Cooke RF, Lamb GC, Vasconcelos JLM, Pohler KG (2021) Effects of body condition score at initiation of the breeding season on reproductive performance and overall productivity of Bos taurus and B. indicus beef cows. Anim Reprod Sci 232:106820. https://doi.org/10.1016/j.anireprosci.2021.106820
16. Dalton JC, Deragon L, Vasconcelos JLM, Lopes CN, Peres RFG, Ahmadzadeh A (2012) Fertility-associated antigen on Nelore bull sperm and reproductive outcomes following first-service fixed-time artificial insemination of Nelore cows and heifers. Theriogenology 77:389–394. https://doi.org/10.1016/j.theriogenology.2011.08.011
17. Dirección Meteorológica de Chile (DME) (n.d.) https://www.meteochile.gob.cl/PortalDMC-web/index.xhtml. Accessed 1 July 2026
18. Eitam H, Brosh A, Orlov A, Izhaki I, Shabtay A (2009) Caloric stress alters fat characteristics and Hsp70 expression in milk somatic cells of lactating beef cows. Cell Stress Chaperones 14:173–182. https://doi.org/10.1007/s12192-008-0070-0
19. Elvinger F, Natzke RP, Hansen PJ (1992) Interactions of heat stress and bovine somatotropin affecting physiology and immunology of lactating cows. J Dairy Sci 75:449–462. https://doi.org/10.3168/jds.S0022-0302(92)77781-9
20. Eslamizad M, Albrecht D, Kuhla B (2020) The effect of chronic, mild heat stress on metabolic changes of nutrition and adaptations in rumen papillae of lactating dairy cows. J Dairy Sci 103:8601–8614. https://doi.org/10.3168/jds.2020-18417
21. Feron S, Cordero RR, Damiani A, Llanillo PJ, Jorquera J, Sepúlveda E, Asencio V, Laroze D, Labbé F, Carrasco J, Torres G (2019) Observations and projections of heat waves in South America. Sci Rep 9:8173. https://doi.org/10.1038/s41598-019-44614-4

22. Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315. https://doi.org/10.1002/joc.5086
23. Garreaud R, Boisier JP, Alvarez-Garreton C, Christie D, Carrasco-Escaff T, Vergara I, Chávez RO, Aldunce P, Camus P, Suazo-Alvarez M, Masiokas M, Castro G, Muñoz A, Zambrano-Bigiarini M, Fuster R, Godoy L (2025) Hyperdroughts in central Chile: drivers, impacts and projections. EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2025-517
24. Gaughan JB, Mader TL (2014) Body temperature and respiratory dynamics in unshaded beef cattle. Int J Biometeorol 58:1443–1450. https://doi.org/10.1007/s00484-013-0746-8
25. Hahn GL, Gaughan JB, Mader TL, Eigenberg RA (2009) Thermal indices and their applications for livestock environments. In: Livestock energetics and thermal environmental management. American Society of Agricultural and Biological Engineers, St. Joseph, pp 113–130. https://doi.org/10.13031/2013.28298
26. Hansen PJ, Arechiga CF (1999) Strategies for managing reproduction in the heat-stressed dairy cow. J Anim Sci 77(Suppl 2):36–50. https://doi.org/10.2527/1997.77suppl_236x
27. Henry B, Charmley E, Eckard R, Gaughan JB, Hegarty R (2012) Livestock production in a changing climate: adaptation and mitigation research in Australia. Crop Pasture Sci 63:191–202. https://doi.org/10.1071/CP11169
28. International Fund for Agricultural Development (IFAD) (2010) Livestock and climate change. https://www.uncclearn.org/wp-content/uploads/library/ifad81.pdf. Accessed 1 July 2026
29. Izquierdo VS, Silva JVL, Ranches J, Santos GCM, Carroll JA, Burdick Sanchez NC, Bittar JHJ, Vendramini JMB, Moriel P (2023) Removing maternal heat stress abatement during gestation modulated postnatal physiology and improved performance of Bos indicus-influenced beef offspring. J Anim Sci 101:skad250. https://doi.org/10.1093/jas/skad250
30. Kadokawa H, Sakatani M, Hansen PJ (2012) Perspectives on improvement of reproduction in cattle during heat stress in a future Japan. Anim Sci J 83:439–445. https://doi.org/10.1111/j.1740-0929.2012.01011.x
31. Kendall PE, Nielsen PP, Webster JR, Verkerk GA, Littlejohn RP, Matthews LR (2006) The effects of providing shade to lactating dairy cows in a temperate climate. Livest Prod Sci 103:148–157. https://doi.org/10.1016/j.livsci.2006.02.004
32. Lees AM, Sejian V, Wallage AL, Steel CC, Mader TL, Lees JC, Gaughan JB (2019) The impact of heat load on cattle. Animals 9:322. https://doi.org/10.3390/ani9060322
33. Livestock Conservation Institute (LCI) (1970) Patterns of transit losses. Livestock Conservation Institute, Omaha
34. Mader TL, Davis MS, Brown-Brandl T (2006) Environmental factors influencing heat stress in feedlot cattle. J Anim Sci 84:712–719. https://doi.org/10.2527/2006.843712x
35. Mader TL, Johnson LJ, Gaughan JB (2010) A comprehensive index for assessing environmental stress in animals. J Anim Sci 88:2153–2165. https://doi.org/10.2527/jas.2009-2586

36. Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 747–846
37. Miranda A, Syphard AD, Berdugo M, Carrasco J, Gómez-González S, Ovalle JF, Delpiano CA, Vargas S, Squeo FA, Miranda MD, Dobbs C, Mentler R, Lara A, Garreaud R (2023) Widespread synchronous decline of Mediterranean-type forest driven by accelerated aridity. Nat Plants 9. https://doi.org/10.1038/s41477-023-01541-7
38. Montiel F, Ahuja C (2005) Body condition and suckling as factors influencing the duration of postpartum anestrus in cattle: a review. Anim Reprod Sci 85:1–26. https://doi.org/10.1016/j.anireprosci.2003.11.001
39. Morton JM, Tranter WP, Mayer DG, Jonsson NN (2007) Effects of environmental heat on conception rates in lactating dairy cows: critical periods of exposure. J Dairy Sci 90:2271–2278. https://doi.org/10.3168/jds.2006-574
40. Mulliniks JT, Sawyer JE, Mathis CP, Cox SH, Petersen MK (2012) Winter protein management during late gestation alters range cow and steer progeny performance. J Anim Sci 90:5099–5106. https://doi.org/10.2527/jas.2012-5535
41. Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U (2010) Effects of climate changes on animal production and sustainability of livestock systems. Livest Sci 130:57–69. https://doi.org/10.1016/j.livsci.2010.02.011
42. Nishimura TK, Martins T, da Silva MI, Lafuente BS, de Garla Maio JR, Binelli M, Pugliesi G, Saran Netto A (2018) Importance of body condition score and ovarian activity on determining fertility in beef cows supplemented with long-acting progesterone after timed-AI. Anim Reprod Sci 198:27–36. https://doi.org/10.1016/j.anireprosci.2018.08.042
43. Polley HW, Briske DD, Morgan JA, Wolter K, Bailey DW, Brown JR (2013) Climate change and North American rangelands: trends, projections, and implications. Rangel Ecol Manag 66:493–511. https://doi.org/10.2111/REM-D-12-00068.1
44. Provolo G, Riva E (2009) One year study of lying and standing behavior of dairy cows in a freestall barn in Italy. J Agric Eng 40:27–33. https://doi.org/10.4081/jae.2009.2.27
45. QGIS Development Team (n (2026) d.) QGIS geographic information system. https://www.qgis.org/. Accessed 1 July
46. Renquist BJ, Oltjen JW, Sainz RD, Calvert CC (2006) Effects of age on body condition and production parameters of multiparous beef cows. J Anim Sci 84:1890–1895. https://doi.org/10.2527/jas.2005-733
47. Reynolds C, Crompton L, Mills J (2010) Livestock and climate change impacts in the developing world. Outlook Agric 39:245–248. https://doi.org/10.5367/oa.2010.0015

48. Rojas-Downing M, Nejadhashemi P, Harrigan T, Woznicki SA (2017) Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag 16:145–163. https://doi.org/10.1016/j.crm.2017.02.001
49. Roldán-Ruiz I, Bernier R, Cornejo-Ovalle M, Squella F, Ruiz N, Avendaño J, Romero O, Ovalle C, Soto P, Jahn E, Demanet R, Covacevich CN, Ruz J (1996) Praderas para Chile. ScienceOpen, Boston
50. Roth Z (2020) Reproductive physiology and endocrinology responses of cows exposed to environmental heat stress: experiences from the past and lessons for the present. Theriogenology 155:150–156. https://doi.org/10.1016/j.theriogenology.2020.05.040
51. Servicio Nacional de Prevención y Respuesta ante Desastres (SENAPRED) (2026) Alerta roja para la Región Metropolitana por calor extremo. https://senapred.cl/alerta/se-declara-alerta-roja-para-la-region-metropolitana-por-calor-extremo-2026-01-14-16-42-34. Accessed 14 January 2026
52. Silveira RMF, McManus C, da Silva IJO (2026) Animal production under climate change: a global scientometric analysis of research structure, thematic evolution, and knowledge gaps. Trop Anim Health Prod 58:282. https://doi.org/10.1007/s11250-026-05071-0
53. St-Pierre NR, Cobanov B, Schnitkey G (2003) Economic losses from heat stress by U.S. livestock industries. J Dairy Sci 86(Suppl 13):E52–E77
54. Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) IPCC (Intergovernmental Panel on Climate Change): the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York
55. Tariq M, Saeed S, Victor KKAS, Fatima A, Mao D (2025) Heat stress and its impact on corpus luteum (CL) function and reproductive efficiency in mammals: a critical review. Reprod Sci 32:977–992. https://doi.org/10.1007/s43032-025-01787-w
56. Thornton PK, Van de Steeg J, Notenbaert A, Herrero M (2009) The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric Syst 101:113–127. https://doi.org/10.1016/j.agsy.2009.05.002
57. Zhao R, Shang Y, Jacinthe PA, Li S, Liu G, Wen Z, Wang Z, Yang Q, Fang C, Song K (2024) Variations in surface area and biogeochemistry of subarctic-arctic lakes established through satellite and in situ observations: an overview of published research from the past 30 years. Sci Total Environ 925:172797. https://doi.org/10.1016/j.scitotenv.2024.172797

Figures

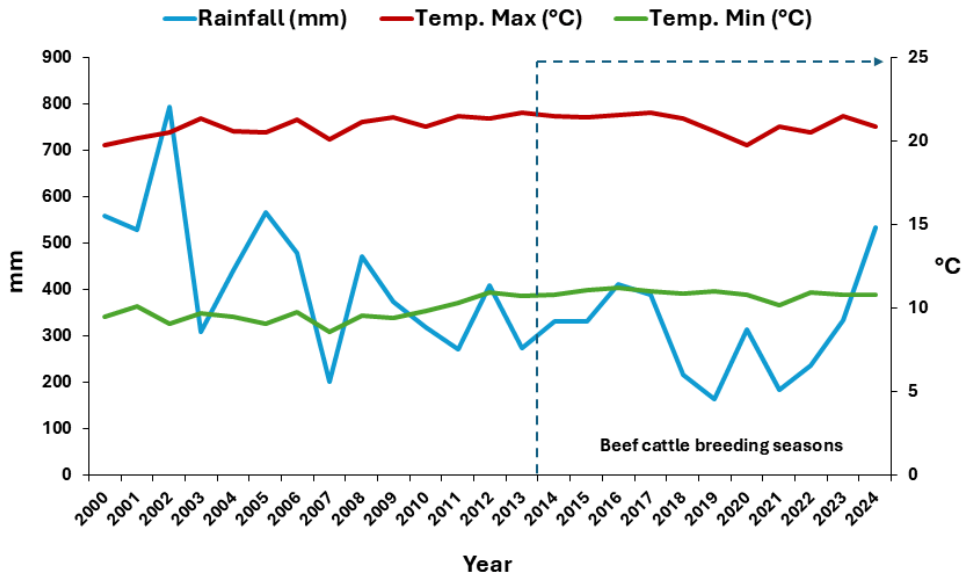


Figure 1

Yearly accumulated rainfall and maximum and minimum temperatures in the central area of Chile during the 2020-2024 period. Highest accumulated rainfall were obtained in 2002 with 792.33 mm and lowest values in 2019 with 162 mm. Maximum temperatures have ranged from averages values of 19.73 to 21.71°C in years 2000 and 2017, respectively. Average minimum temperature ranged from 9.01°C (2002) to 11.22 °C (2016) with values of 10.75 °C during 2024. Breeding seasons included in the study are demarcated with discontinuous line.

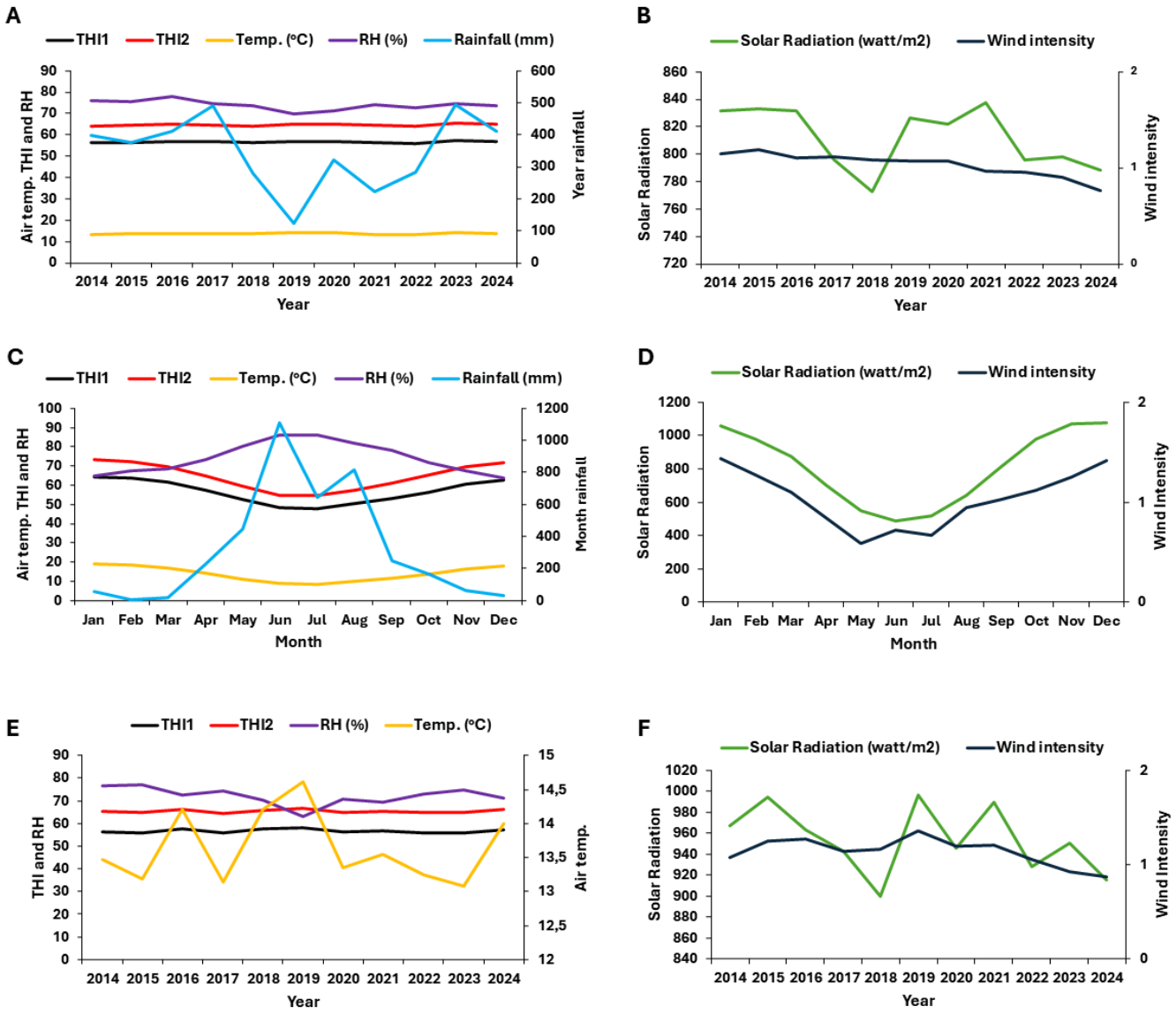
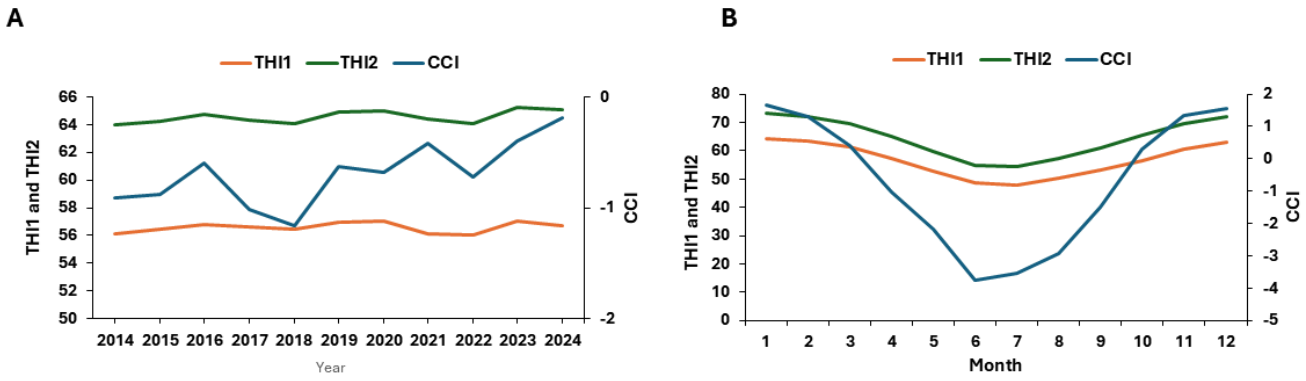


Figure 2

Yearly and monthly climate variables including air temperature, relative humidity, solar radiation and wind intensity, and THI1 and THI2 for the 2014-2025 period in the central area of Chile. Air temperature ranged yearly from 13.4 (2014) to 14 °C (2023) and monthly from 8.28 (July) to 18.8 °C (January) (A,C). Highest and lowest yearly relative humidity values were 77.2 % (2016) and 69.88 % (2019). Monthly, highest and lowest relative humidity values were 85.95 % (July) and 63.91 % (December). Solar radiation values ranged yearly from 772 to 837.33 watt/m2 (2021) and monthly from 488.17 (June) to 1078.72 (December) (B,D). Wind intensity values ranged yearly from 1.18 (2015) to 0.76 (2024) and monthly from 0.59 (May) to 1.43 (January). Accordingly, THI1 values ranged from 56.07 to 57.73 in years 2022 and 2023, respectively (2A). This index had more variation throughout the year with highest values in January (63.52) and lowest value in July (47.79) (2C). In comparison, TH2 values ranged from 63.96 to 65.2 for

years 2014 and 2023, respectively. Moreover, variation of TH2 among months was 74.56 to 54.42 for February and July, respectively. Analysis of yearly temperature during breeding seasons (September to November) indicated that highest values were detected on 2016 (14.2) and 2019 (14.6) and lowest values on 2017 (13.1) and 2023 (13.1) (2E). Relative humidity values were highest on in 2015 (77.2) and lowest in 2019 (63.1). THI1 and TH2 values ranged from 55,9 (2015) to 58 (2019) and from 64.6 (2017) to 66.6 (2019), respectively. Yearly solar radiation ranged from 994.2 (2015) to 899.7 (2018). Highest and lowest wind intensity values were detected in 2016 (1.27) and (2024) 0.87, respectively (2F).



Item	r_p	df	t	P
Monthly				
THI1 and THI2	0.99	10	43.8	<0.001
THI1 and CCI	0.97	10	12,7	<0.001
THI2 and CCI	0.98	10	18.1	<0.001
Yearly				
THI1 and THI2	0.94	9	8.4	<0.001
THI1 and CCI	-0.31	9	-0.96	0.362
THI2 and CCI	0.0225	9	0.0674	0.947

Figure 3

Pearson correlations between yearly and monthly values of THI1, THI2 and CCI during the 2014-2024 period in the central area of Chile. Monthly THI1 and THI2 (0.99), THI1 and CCI (0.97) THI2 and CCI (0.98) and yearly THI1 and THI2 (0.94) correlations were significant (A).