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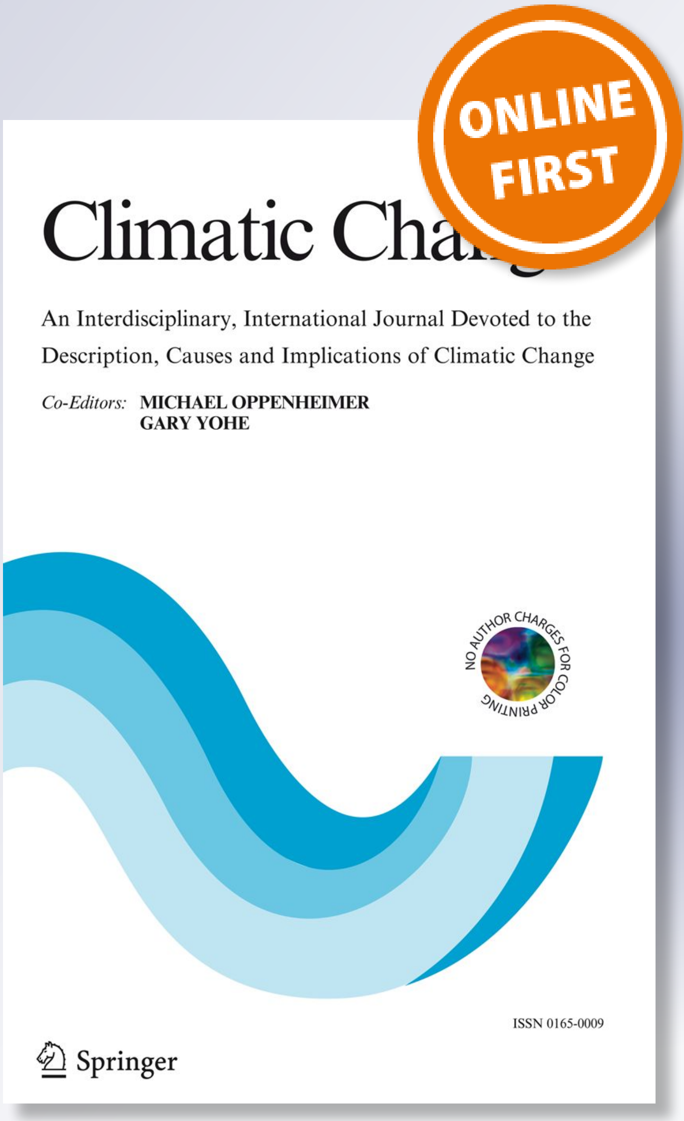

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Impacts of climate change on bovine livestock production in Argentina

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Abstract
The study considers the most important livestock regions of Argentina and the correlation between livestock and climate units. The conceptual scheme designed to understand these effects of climate elements on cattle describes a basic direct action by the air temperature in the environment in which they develop, considering temperature as the limit for the distribution of breeds and other action through its effects on vegetation and forage resources that will be available. The work done here shows a shift of the livestock regions southward and eastward simultaneously in the region under consideration. This is a consequence of the displacement towards the south of the isotherm of 26 °C and towards the east of the humidity indices, co-incidentally with the displacement of the isohyets of 600 and 1200 mm. As a consequence of the climate change, according to the CCSM4 climate model, in the near and far future under two emission scenarios, the regions suitable for tropical livestock (breeds with high heat tolerance as the *Bos indicus*) will extend to the southeast, displacing and reducing the regions suitable for European breed cattle. The displacement of the higher rainfall area mainly to the east could benefit livestock production by increasing forage and reducing livestock feed requirements.

1 Introduction

The objective of the paper is to define the zoning for bovine livestock according to elements of climate of direct action such as temperatures and indirect action through its effect on potential availability of forage, which is related to extensive, semi-intensive, and intensive economic production systems.

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Bovine livestock production remains one of the most important economic sectors and important source of export earnings in Argentina. With an economy highly dependent on agriculture and cattle raising, Argentina is likely to be strongly impacted by climate change through its effects on production and changes in the livestock breeds currently used. Livestock producers in Argentina are already experiencing climate change and variability, and threats to production are expected to multiply in the short and medium term.

We designed a conceptual scheme to facilitate the understanding of the effects of climate on cattle. Cattle are warm-blooded animals, and under certain environmental conditions, they have the necessity and ability to control their body temperature within a narrow range. This is a priority demand for maintenance and survival, so when gaining or losing heat in the body heat balance, the thermoregulation control of the animal has mechanisms to maintain body temperature, relegating other priorities such as gestation, growth, lactation, fat accumulation, and nutrients (Loewer and Parsch 1995a, b), with the consequent effect on their production characteristics. GRAZE (Graze Beef Forage Simulation Model) (Loewer and Parsch 1995a, b) was used to study and interpret the effects of climate change on cattle breeding and grazing in the prioritized areas. The model was developed by the Southern Regional Project S-221 (University of Florida/University of Arkansas).

The different physiological characteristics of bovine breeds have been shaped by centuries of selection in their places of origin. Bovine behavior varies from a great tolerance to low temperatures and less tolerance to high temperatures such as with British and European breeds and an opposite tolerance conditions in the case of *B. indicus* breeds.

The genetic characteristics of cattle and their relation to climate define much of its production capacity. Therefore, climate is one of the main risk factors involved in bovine cattle production. Climate change is one of the most studied topics in the last decades due to its socioeconomic, environmental, and biological implications. More specifically, the livestock area is strongly controlled by weather and climate and they are highly vulnerable to climate change (IPCC 2014).

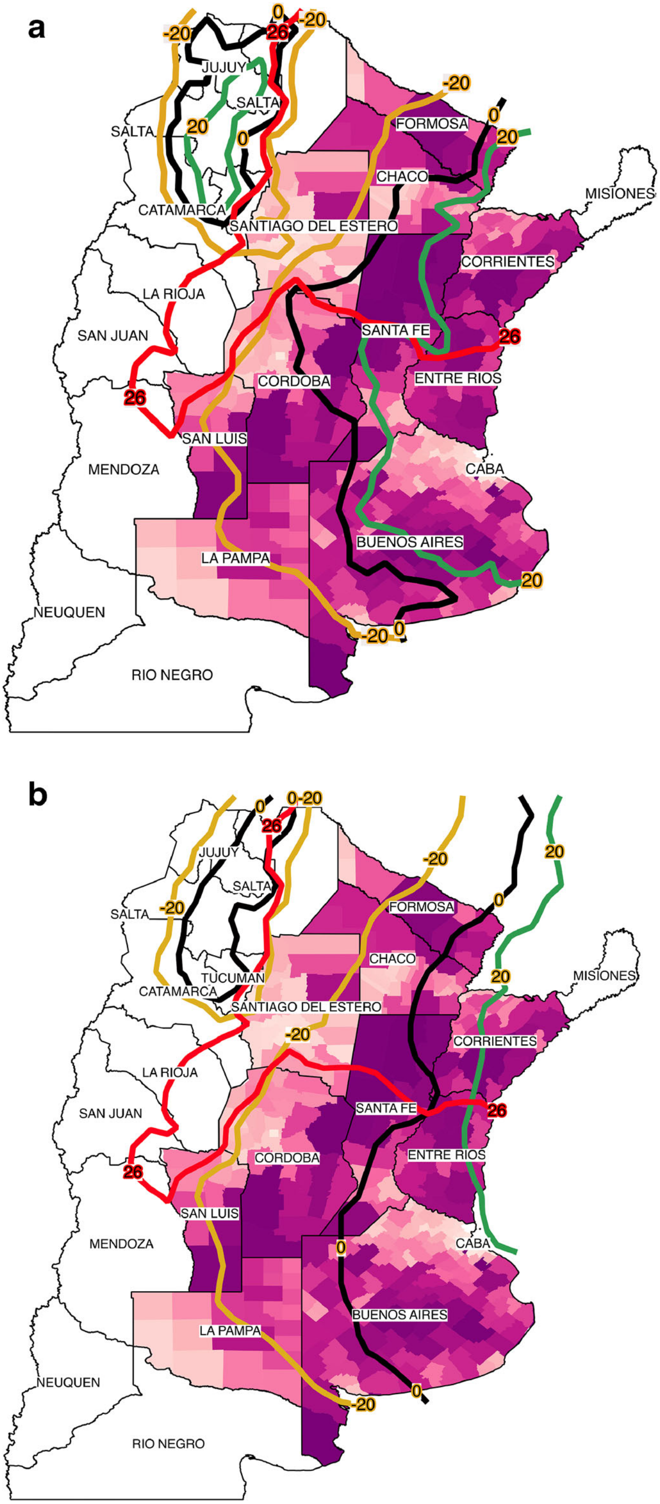
Regarding the present climate, previous studies have shown that Humid Pampa, an area comprised of various provinces of Argentina, is one of the regions where the biggest changes occurred in the climate during the last 30 years of the twentieth/twenty-first centuries (Barros et al. 2000; Nuñez et al. 2008).

The study area is the most important livestock region in Argentina and the correlation between livestock and some climate parameters were used to estimate the climate change impacts on bovine livestock production (Argentina climate change report to UNCCF, 3CN, 2015).

2 Study area characterization

The study area includes the Argentinean provinces of Entre Rios, Santa Fe, Cordoba, Buenos Aires, Formosa, Chaco, Santiago del Estero, Corrientes, and La Pampa (Fig. 1a, b) where the biggest production of bovine cattle is concentrated. In the last 50 years, this region had important changes in production systems. These changes were associated with changes on

Fig. 1 **a** Agreement of the livestock regions with the provincial stocks (more livestock = more intensive color) and CCSM4 climatic areas (isotherm 26 °C: red; Thornthwaite index: brown, black, and green). **b** Agreement of the livestock regions with the provincial stocks (more livestock = more intensive color) and CRU climatic areas (isotherm 26 °C: red; Thornthwaite index: brown, black, and green)


a
JUJUY
SALTA
SALTA
CATAMARCA
SANTIAGO DEL ESTERO
FORMOSA
CHACO
MISIONES
CORRIENTES
LA RIOJA
SAN JUAN
SANTA FE
ENTRE RIOS
CORDOBA
SAN LUIS
MENDOZA
CABA
BUENOS AIRES
LA PAMPA
NEUQUEN
RIO NEGRO
-20
0
26
20
b
TUCUMAN

some climatic parameters, specifically in the study region; spring and summer rains increased from 10 to 50% since the 1960s and 1970s, while the minimum temperatures increased up 1.9 °C and maximum decreased to 2.0 °C (Barros et al. 2000; Nuñez et al. 2008).

As shown in Fig. 2 a and b, the stock of cattle in Argentina grew from something more than 13 million heads in the year 1875, reaching a maximum peak of more than 61 million in 1977, remaining in 2015 at approximately 52.9 million heads of cattle.

The figures show that the growth has presented two well-defined phases, the first with a uniform positive slope that extended from the beginning of the measurement until the year 1966 and the second from 1967 to the present, characterized by a neutral or slightly negative trend between extremes, with a strong variability, in the order of 13 million heads, with a maximum of 60 and 1 million and minimum of 48 million.

This turning point is linked to the changes that occurred in that decade in the world meat trade due to the variations in the international demand of this product with new sanitary standards, the creation of the "European Common Market," and fundamentally, the appearance, in 1967, of the foot and mouth disease (aftosa fever) in Great Britain, important buyer of Argentine products, which led her to sacrifice large quantities of her own cattle and deny the importation of meat with bone, generating the need for changes in the Argentine industry. These conditions altered the market and forced the decline of exports from Argentina, which in the year 1970 was displaced as the world's leading meat exporter (de las Carreras and Gorelik 2012).

For the period from 1875 to 1966, the linear regression shows a good adjustment and indicates a fairly stable annual growth of approximately 331,000 heads per year.

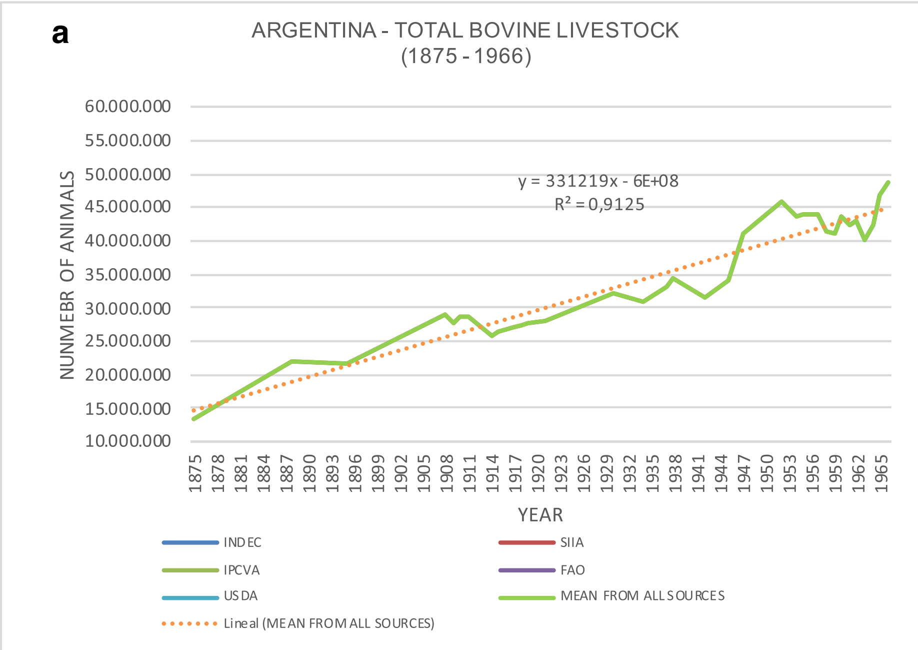
For the following period from 1967 to 2015, the main characteristic has been the strong variability of bovine stocks, with a slightly decreasing linear adjustment (3CN 2015b).

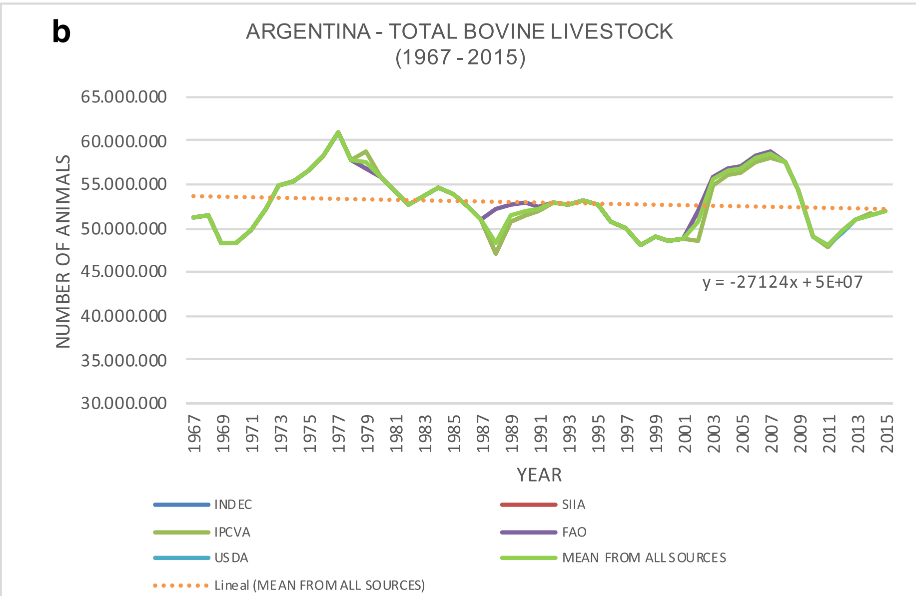
Livestock in Argentina has been developed basically from livestock introduced in the foundational principles of the region ("Criollo" cattle) and with the subsequent entry of high value breeds of European origin in the region known as "Pampa Húmeda" (PH), an extensive plain of temperate climate that extends over the center of the country, the whole of the province of Buenos Aires, the center and the south of the province of Santa Fe, the southern and central-eastern sectors of the province of Córdoba, and the eastern third of the province of La Pampa (see Fig. 1 with provinces).

Due to its characteristics, it could be defined as an activity that combines the factors and steps necessary for the production of cuts of high-quality beef, traditionally on the basis of an extensive system of breeding using exclusively the pasture as food and integrating the processes of breeding, rearing, wintering, slaughtering, and sale.

Fig. 2 **a** Total bovine livestock and trends from year 1875 to 1966. Sources: INDEC: Argentina. National Institute of Statistics and Census, Argentina. https://www.indec.gob.ar IPCVA: Institute for the Promotion of Argentine Beef. http://www.ipcva.com.ar USDA: U.S. Department of Agriculture. https://www.usda.gov FAO: Food and agricultural organization of the United Nations. http://www.fao.org/home/en/ SIIA: Ministry of Agro-Industry, Argentina. https://www.agroindustria.gob.ar/datosabiertos/. **b** Total bovine livestock and trends from year 1967 to 2015. Sources: INDEC: Argentina. National Institute of Statistics and Census, Argentina. https://www.indec.gob.ar. IPCVA: Institute for the Promotion of Argentine Beef. http://www.ipcva.com.ar. USDA: U.S. Department of Agriculture. https://www.usda.gov. FAO: Food and agricultural organization of the United Nations. http://www.fao.org/home/en/. SIIA: Ministry of Agro-Industry, Argentina. https://www.agroindustria.gob.ar/datosabiertos/

With the growth of the livestock through the years and its expansion to extra Pampean areas, *B. indicus* breeds were also incorporated, more tolerant to environmental conditions dominated by higher temperatures. The average stock for the period 1967–2015 has been 52.9 million heads of cattle, with a standard deviation of 3.3 million.





Different conditions, fundamentally economic, have driven changes in the factors of production involved, modalities that by making more "intensive" use of capital and labor, with a less intensive use of land, have gone to the so-called intensive production system modality (or semi-intensive in other cases) to fattening or finishing practices with concentrated foods, mainly grains and their by-products.

The location of these establishments is concentrated (86%) in the four main provinces of the PH, with a replenishment of hacienda concentrated between autumn and winter (months of April to September).

Separately, there is another relevant activity, such as that for milk production, usually carried out in specialized establishments called "Tambos," and with a preponderance of dairy farming.

3 Relationship of temperature and humidity with cattle

Table 1 summarizes the main responses of the animal biotypes versus temperature, it must be noted that there are differences in the reaction between breeds of the same origin and even between individuals of the same breed (Yousef 1985; Blackshaw and Blackshaw 1994).

Similarly, the effects of climate on vegetation and therefore, feed resources that are available are an important type of indirect action on cattle, by conditioning the availability of nutrients and energy. To estimate the interaction weather—fodder, we analyzed their potential spatial distribution and characterization from a series of meteorological observations using climate indices.

We have used the modified Thornthwaite Humidity Index to characterize the climatic regions due to the simplicity of calculation and interpretation (mainly because the variables used by this index are available in the climatic models at the time of doing this work). Table 2 shows the defined conditions for livestock according to the selected water index (Burgos 1958; Thornthwaite 1948). Based on two elements (temperature and water index), it is possible to formulate a climatic zoning for cattle grazing.

Figure 1a shows the 26 °C isotherm and the water indices calculated using the above-described methodology. The basic information was obtained from the climate model CCSM4 for the period 1960 to 2010. Figure 1b shows the same isotherm and water indices using observations from CRU database (Climatic Research Unit, University of East Anglia, http://www.cru.uea.ac.uk/data). It can be seen that the mean isotherm of 26 °C (red line) of the hottest month is the limit from which, to the north, *B. indicus* breeds are in harmony and comfort with their environment and without food restrictions to develop all its productive potential. Towards the south of this isotherm, breeds of British and European origins are suitable for production. In these cases, the comfort range is for lower temperatures. The same

Table 1 Summary of main responses of the animal's biotypes versus temperature (Yousef 1985; Blackshaw and Blackshaw 1994)

Breeds	Limited conditions	Comfort	Increase in respiratory rhythm	Increase internal body temperature
British/European	Below 0 °C	Between 1 and 21 °C	Between 21 and 27 °C	Between 27 and 32 °C
Indicus	Below 10 °C	Between 10 and 27 °C	Between 27 and 32 °C	Between 32 and 38 °C

Table 2 Summary of main conditions for livestock activity versus water index Burgos 1958; Thornthwaite 1948)

Conditions for livestock activity	Water index		Thornthwaite climates
	from	to	
Ideal	0	20	Sub-humid-humid
Hypo calcemic grazing	20	40	Humid
Normal grazing with supplementation	0	− 20	Sub-humid-dry
Grazing with continuous supplementation	− 20	− 40	Semi-arid

can be said about the areas included in the water indices, which define the grazing conditions already stated in the corresponding table.

From here on, it is defined as "normal grazing" or "grazing" the grazing of the forage produced by pastures, applying the logic of dividing the paddock to graze in areas of different quality and density, among which the animal will select, under the premise of maximizing the intake of dry material, and "grazing with supplementary feed" as obtained from another source in the periods of scarce forage production.

In this way, it is possible to define the following livestock regions based on climatic conditions:

1. Tropical climate livestock, with normal grazing, occupies the north of Entre Ríos and Santa Fe, eastern-center of Chaco and Formosa, and west center of Corrientes provinces (see Fig. 1a).
2. Tropical climate livestock, with grazing with supplementary feed, occupying the northwest of Córdoba, east of La Rioja, southeast of Catamarca, Santiago del Estero, and north of Chaco and Formosa (see Fig. 1a).
3. Tempered climate livestock, with normal grazing, occupies Buenos Aires; east of La Pampa; center, east, and south of Córdoba; south of Santa Fe; and south of Entre Ríos (see Fig. 1a).
4. Tempered climate livestock, with grazing with supplementary feed, occupying the west and south of the country, up to the mean isotherm of 5 °C (not shown) of the coldest month.

Argentina has different livestock regions that differ in their pasture production potential and in their quality, so there is also a regional distribution of livestock activities. "Pampa Húmeda" (PH) concentrates the breeding activity in the areas with soil limitations and the activity of rearing and fattening, in the soils of highest aptitude in rotations between bovine livestock and agriculture. In the PH, the animals are taken to areas of higher quality soils, where they consume annual and perennial pastures throughout the year and receive supplementary feed only occasionally. Oats, rye, and barley are the annual fodder used during winter and sorghum or corn during the summer. The main species of the pastures are *Festuca arundinacea*, *Dactylis glomerata*, *Phalaris aquatica*, *Lolium perenne*, and *Bromus* sp., *Agropyron elongatum* among the grasses and *Trifolium pratense*, *T. repens*, *Medicago sativa*, and *Melilotus officinalis* among the legumes.

The use of supplementary feed, hay or silages, is necessary in the western sector of the PH and extra Pampean areas, where the Thornthwaite Water Index has values from 0 to − 20, with soils that have a water balance negative during some months of the year.

The production of forage varies from 2 to 12 tons of dry matter per hectare, depending on the soils and location and the production of meat from 80 to 500 kg/ha and year. (Rearte 2007).

4 Present and climate projections for near and far future

Previous studies have shown that southeast of South America, an area comprised by Argentina, Uruguay, and the south of Brazil, is one of the regions in the world where the greatest changes in climate have been recorded during the last 30 years. The last results indicate that the climatic conditions in Argentina persist at least from 30 years ago. The observed changes in temperature show that between 1960 and 2010, there was an average annual temperature increase between 0.5 and 1 °C in Argentina. Heat waves increased significantly in the north and east of the country and frosts decreased in most of the country. Precipitation in the period 1960–2010 over Argentina increased in almost the entire country although with interannual variations, except in the Patagonian Andes where annual rainfall decreased. The change in precipitation observed is more intense and more frequent in a large part of the country (Argentina climate change report to UNCCF, 3CN 2015).

Figure 3 represents the annual mean maximum temperature and annual mean precipitation for the present climate obtained using CRU database. On the left of Fig. 3, the annual mean maximum temperature for Argentina is shown with values greater than 30 °C in the north and values less than 0 °C in the south. The average annual precipitation values are also shown in the same figure. The distribution of precipitation in Argentina is not as homogeneous as temperature (function of insolation and slope of the soil). In North and Central Argentina, precipitation changes

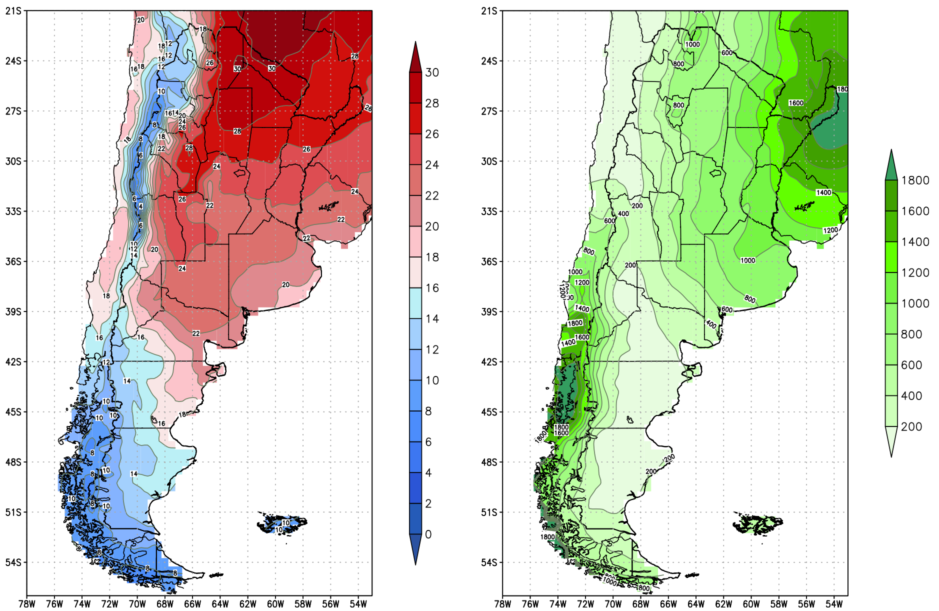


Fig. 3 Annual mean maximum temperature period 1960–2010 (left). Annual mean precipitation period 1960–2010 (right)

from west to east, with values less than 800 mm in the west, exceeding 1800 mm in the east. In the center and south of Argentina, changes in the precipitation are opposite to that observed in the north, with greater values at the west (more than 1800 mm) and values less than 200 mm in the east.

The impacts of climate change on bovine cattle zoning were estimated for the present time (1960–2010) and for the near future (2015–2039) of interest for "adaptation policies," and the far future (2075–2099) of informative nature over the long term. Two emission scenarios of greenhouse gases were used, a moderate emissions scenario (RCP 4.5) and a higher emissions scenario (RCP 8.5) where RCP means "Representative Concentration Pathways" (van Vuuren et al. 2011).

The methodology of ensembles for future climate projection is recommended by the IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections (Knutti et al. 2010). The disparity in the representation of the regional climate by the models analyzed was verified during the Argentinian Third National Communication on Climate Change (3CN 2015a). For example, in the case of precipitation, the percentage errors vary from almost 0 to 46% in the humid and central regions (our study area) and to 185% in the Andes and Patagonia regions of Argentina. In general, only a small number of models correctly adjust to the present climate observed in each region. Therefore, it is better to project the regional climate with these models and not to do it with the average of all the models since this average can be affected by models with a very poor representation of the regional climate (3CN 2015a).

Climate changes were projected using the CCSM4 climate model of the National Center for Atmospheric Research (NCAR, USA) because it was shown that the best among 24 climate models from CMIP5 (Coupled Model Intercomparison Project 5) and CLARIS-LPB (A Europe-South America Network for Climate Change Issues and Impacts Assessment—La Plata Basin Project) was assessed for the present time in the region after a quantile-mapping bias correction (Thrasher et al. 2012) using CRU (Climate Research Unit) observations. A comprehensive evaluation index has been defined by averaging temperature and precipitation indices in each of the regions studied during the Argentina Third National Communication of Climate Change (3CN 2015a). This index is the single index model validation (IUVM), which varies between 0 and 1, where values close to 0 are indicators of poor performance, while the greater the ability of the model to represent the observed climate, IUVM approaches 1. Table 3 represents the values of the IUVM for each studied region and each model analyzed in the 3CN. As shown in the table, the weighted IUVM for "Centro" and "Húmeda" region (our area of interest) is the highest for CCSM4 model (Rolla et al. 2018).

The climate database at Centro de Investigaciones del Mar y la Atmosfera (CIMA) (http://3cn.cima.fcen.uba.ar) was used. Calibrated outputs temperature and precipitation from the CCSM4 model for the present and future periods and for the two emission scenarios are available in this database. The CCSM4 model output after calibration over the region for the present time had the best agreement with CRU observations (IUVM = 0.81).

5 Assessment of climate change impacts on cattle

The variables from the climate model that affect the development of bovine cattle were considered, specifically temperature and humidity, as well as their changes in the near and far future.

In the absence of moisture measurements, the use of water indexes was considered as appropriate, estimated with output variables provided by CCSM4 model. Among the possible indices, the Thornthwaite Hydric Index (Thornthwaite 1948) was used for its ease in treating humidity and for the feasibility of computing it from the variables provided at 3CN database.

Table 3 Single index model validation (IUVM). Classified descendent by IUVM weighted. (Rolla et al. 2018)

Models	Regions				IUVM mean	IUVM std dev	IUVM weighted	Ranking
	Patagonia	Andes	Centro	Húmeda				
CCSM4	0.36	0.51	0.56	0.91	0.59	0.23	0.81	1
MRI/JMA	0.48	0.54	0.57	0.88	0.62	0.18	0.79	2
NorESM1-M	0.45	0.51	0.56	0.62	0.54	0.07	0.60	3
CNRM-CM5	0.35	0.15	0.9	0.47	0.47	0.32	0.60	4
MPI-ESM-LR	0.31	0.52	0.6	0.55	0.5	0.13	0.57	5
MRI-CGCM3	0.51	0.51	0.7	0.49	0.55	0.10	0.55	6
IPSL-CM5A-MR	0.22	0.93	0.48	0.53	0.54	0.29	0.52	7
HadGEM2-CC	0.43	0.47	0.36	0.57	0.46	0.09	0.51	8
RegCM3-HadCM3	0.14	0.21	0.48	0.48	0.33	0.18	0.48	9
CSIRO-Mk3–6-0	0.52	0.46	0.71	0.38	0.52	0.14	0.48	10
LMDZ-IPSL	0.15	0.19	0.66	0.34	0.34	0.23	0.44	11
LMDZ-ECHAM5	0.28	0.5	0.42	0.42	0.41	0.09	0.42	12
GFDL-ESM2G	0.52	0.3	0.63	0.31	0.44	0.16	0.41	13
RCA-ECHAM5–3	0.48	0.17	0.4	0.4	0.36	0.13	0.40	14
RCA-ECHAM5–2	0.47	0.17	0.4	0.4	0.36	0.13	0.40	15
HadGEM2-ES	0.44	0.43	0.49	0.32	0.42	0.07	0.37	16
MRI/JMA LR	0.24	0.37	0.23	0.43	0.32	0.10	0.37	17
RCA-ECHAM5–1	0.3	0.14	0.36	0.34	0.29	0.10	0.35	18
REMO_ECHAM5	0.66	0.4	0.36	0.3	0.43	0.16	0.32	19
RegCM3-ECHAM5	0.19	0.37	0.26	0.25	0.27	0.07	0.25	20
PROMES-HadCM3	0.51	0.47	0.34	0.16	0.37	0.16	0.21	21
INMCM4	0.37	0.37	0.23	0.14	0.28	0.11	0.17	22
MIROC5	0.35	0.2	0.3	0.11	0.24	0.11	0.17	23
MM5-HadCM3	0.58	0.31	0.12	0.12	0.28	0.22	0.12	24

The calculation of the values of the Thornthwaite Water Index based on the temperatures and precipitation delimited the spatial variations of the livestock regions previously defined. This methodology was applied both for the present time and those corresponding to the near future (years 2015–2039) and far future (years 2075–2099), with concentration for emission of gases corresponding to RCP 4.5 and RCP 8.5.

As a function of humidity and temperature, the study region is classified in sub-humid-humid climate (indices range from 0 to 20) and sub-humid-dry (indices range from − 20 to 0). Those areas included the major number of cattle in the study region, as it can be seen in Fig. 1 a and b.

6 Tropical livestock regions

Following the previous region definitions, according to the climatic variables for present and future climates, the livestock distribution in the study area is as follows (Fig. 4):

6.1 Present climate

a. Eastern region: With normal grazing, it is located to the north of the mean isotherm of 26 °C of the hottest month and limits to the east with the Water Index (WI) + 20 and to the west with the WI 0, occupying north of the province of Santa Fe, southeast of Chaco, and east of Formosa (see Fig. 4 upper left panel).

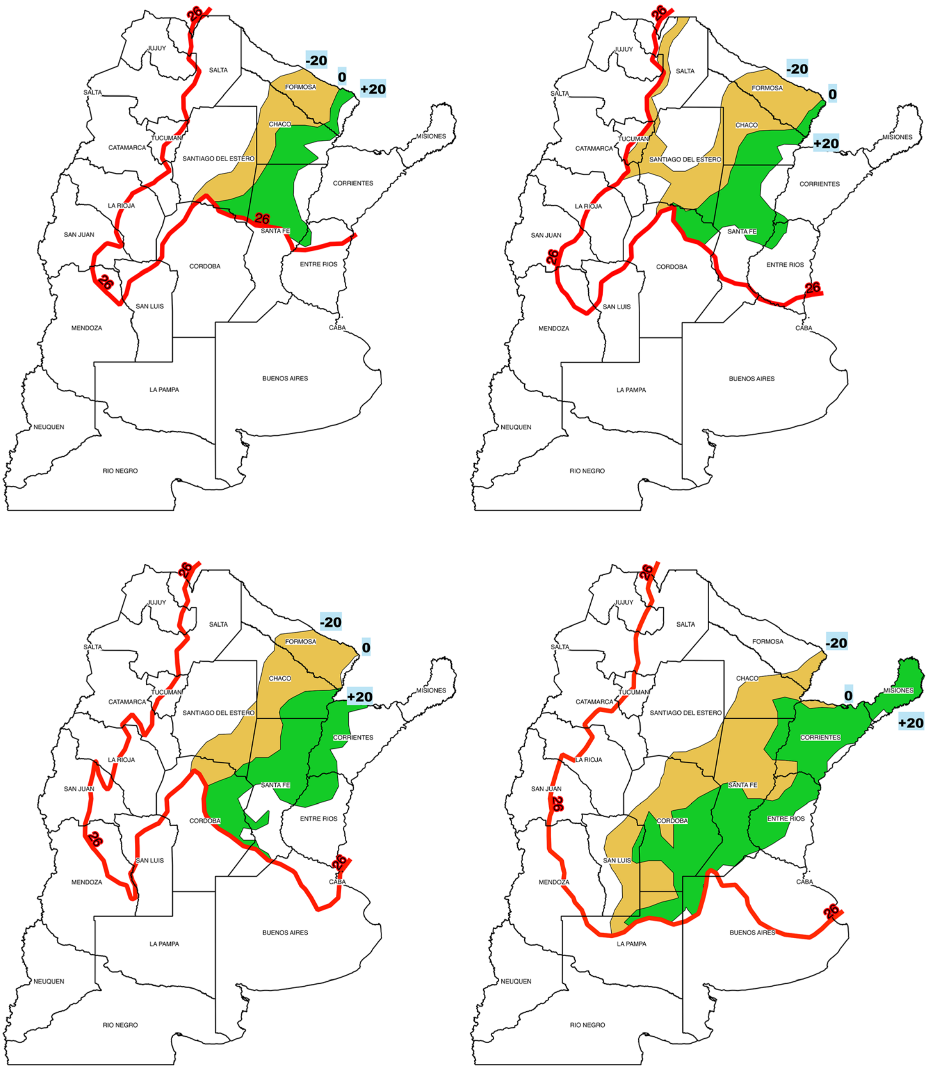


Fig. 4 Tropical livestock region. CCSM4 climate model. Present climate (upper left panel). Near future RCP 4.5 (upper right panel). Far future RCP 4.5 (lower left panel). Far future RCP 8.5 (lower right panel)

b. Western region: With grazing with supplementary feed, it is located north of the mean isotherm of 26 °C of the hottest month and limits the east with the WI 0 and west with the WI −20, occupying the southeast of Santiago del Estero, the center of Chaco, and the center of Formosa.

6.2 Near future (RCP 4.5 and RCP 8.5)

Since there are no large differences between low and large emission scenarios for climate projections, only the results for the RCP 4.5 scenario (low emissions) are discussed here.

a. Eastern region: It shows a small displacement towards the east in its upper limit, while in its middle and lower region it extends towards the southwest, accompanying the displacement of the 26 °C isotherm (see Fig. 4 upper right panel).
b. Western region: This sub-region extends its southern part to the west. The displacement of the 26 °C isotherm moves southeast reaching south of Entre Ríos.

6.3 Far future (RCP 4.5)

a. Eastern region: It shows an important eastward displacement occupying the western half of Corrientes and northwest of Entre Ríos provinces. In its lower part, it extends towards the southwest, occupying the northeast of Córdoba province (see Fig. 4 lower left panel).
b. Western region: In the North of the region, there was a shift to the East.

The 26 °C isotherm continues its displacement in a southwest direction, occupying the province of Santa Fe and part of the provinces of Cordoba and part of Buenos Aires.

6.4 Far future (RCP 8.5)

a. Eastern region: It maintained its tendency of significant displacement towards the east, occupying all Corrientes, Misiones, the west center of Entre Ríos, south center of Santa Fe, east of Córdoba, northwest of Buenos Aires, and northeast of La Pampa (see Fig. 4 lower right panel).
b. Western region: This sub-region continued its displacement, occupying center-east of San Luis, north of La Pampa, north of Córdoba, southeast of Santiago del Estero, southeast of Chaco and Formosa, and north of Santa Fe. The 26 °C isotherm continues to move southward, reaching the center of Buenos Aires, north of La Pampa, and the entire province of Córdoba.

7 Regions for temperate livestock

7.1 Present climate

a. Eastern region: With normal grazing, it is located to the south of mean isotherm of 26 °C and limits to the east with the WI +20 and to the west with the WI 0, shows the aforementioned displacement due to the climate model, occupying southeast, center, and northwest of the province of Buenos Aires, south of Santa Fe, and northeast of Córdoba (see Fig. 5 upper left panel).
b. Western region: With grazing with supplementary feed, limits to the east with the Water Index (WI) 0 and to the west with the WI −20, occupying west and southwest of the province of Buenos Aires, the extreme southwest of Santa Fe, northeast of La Pampa, east of San Luis, and almost whole Córdoba.

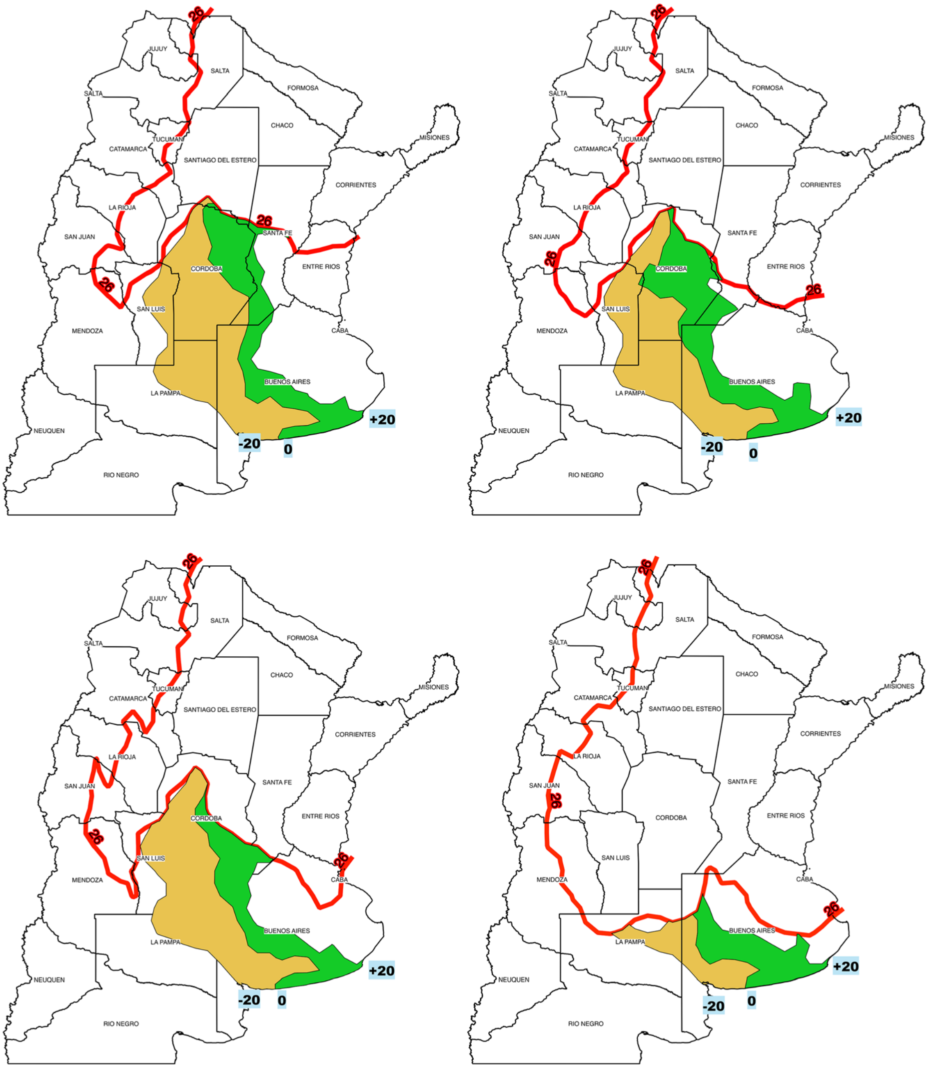


Fig. 5 Temperate livestock region. CCSM4 climate model. Present climate (upper left panel). Near future RCP 4.5 (upper right panel). Far future RCP 4.5 (lower left panel). Far future RCP 8.5 (lower right panel)

7.2 Near future (RCP 4.5 and RCP 8.5)

The corresponding RCP4.5 is described since the delimitation and consequent regionalization for this horizon with RCP8.5 presents minimal differences with this, which do not merit a detailed description.

a. Eastern region: With normal grazing and without reserves, it is located to the south of mean isotherm of 26 °C, which is moving to the north of Buenos Aires. This sub-region slightly increases the occupied area compared to the present time Córdoba (see Fig. 5 upper right panel).

b. Western region: Its eastern front moves westward, while the western boundary remains in a similar position. This sub-region slightly decreases the occupied area compared to the present time.

7.3 Far future (RCP 4.5)

a. Eastern region: The southward advance of the 26 °C isotherm, which reaches almost the center of Buenos Aires. This sub-region decreases the occupied area compared to the present time (see Fig. 5 lower left panel).

b. Western region: This sub-region does not show larger displacements. Again, it decreases the occupied area compared to the present time.

7.4 Far future (RCP 8.5)

a. Eastern region: This scenario of greater emission shows an important advance towards the south of mean isotherm of 26 °C, leaving areas of northeastern Buenos Aires and northern Pampas favorable for tropical livestock (see Fig. 5 lower right panel).

b. Western region: This sub-region reduces its area and maintaining the same northwest-southeast orientation over Buenos Aires and La Pampa.

8 Conclusions

The Pampas and neighboring regions are among the major livestock regions in the world; a source of export earnings in Argentina originated in this region. The beef cattle production is an important agriculture sub-sector with about 200,000 beef producers managing about 52 million heads of cattle (FAO 2017).

Climate and livestock production models provide some broad projections on the effects of climate change, although these will vary with location, soil type, and management (Sudmeyer et al. 2016).

The study considers the most important livestock regions and the correlation between livestock and climate units. This allows to consider the livestock regions as homogeneous areas and to be analyzed under climate change impact.

The conceptual scheme designed to understand these effects of climate elements on cattle describes a basic direct action by the air temperature in the environment in which they develop, considering temperature as the limit for the distribution of breeds, and other action through its effects on vegetation and forage resources that will be available.

The work done here shows a shift of the livestock regions southward and eastward simultaneously. This is a consequence of the displacement towards the South of the isotherm of 26 °C and towards the east of the humidity indices, co-incidentally with the displacement of the isohyets of 600 and 1200 mm. As it was previously described, the highest spatial density of cattle is between the water indexes − 20 and + 20 that coincide approximately with the above isohyets.

As a consequence of the climate change, according to the CCSM4 climate model, in the near and far future under two emission scenarios, the regions suitable for tropical livestock (breeds with high heat tolerance as the *Bos indicus*) will extend to the south-east, displacing and reducing the regions suitable for European breed cattle. The displacement of the higher rainfall area mainly to the east could benefit livestock production by increasing forage and reducing livestock feed requirements.

Regarding the effect of climate change on the spatial distribution of livestock, given the ranges in years of the horizons of each proposed emission scenario and the relatively short life of these animals do not assume that large physical movements of tropical cattle (*Bos indicus*) advancing in favor of temperature increases, but foresee a migration of genes from these breeds to those of temperate climates (*Bos taurus*).

Through the genetic incorporation of the physiological characteristics of tropical cattle, biotypes obtained are characterized by their high production, even in high temperatures and adverse environmental conditions, with greater resistance to diseases than the original British breeds.

As an example of this, we can mention the two synthetic breeds obtained from the introduction of Brahman blood, mainly, and Nelore (*Bos indicus* sp.) in the excellent livestock Hereford and Aberdeen Angus (*Bos taurus* sp.), named Braford and Brangus respectively.

Both synthetic breeds have achieved important participation in stocks in both tropical and temperate livestock, anticipating the mentioned gene migration, being accepted by livestock producers as a new production tool superior to those previously existing.

Another interesting example of this genetic migration is the development of the Australian Milking Zebu (AMZ) breed, incorporating the advantages of *B. indicus* into the Jersey dairy breed (Hayman 1972).

The quality of Argentine meats produced on pasture is traditionally considered as a very good quality in the world and recognized for their lower content of fat, saturated fatty acids, and cholesterol (Garcia and Casal 1992). In spite of climate change, the above characteristics are still observed in the synthetic breeds Bradford and Brangus (Asociación Braford Argentina 2016; de Freitas et al. 2013) and surely, the maintenance at that level of quality will be an important part of future genetic development.

Consequently, the analysis of the new interaction between soils and climate by these displacements with an advance towards the west of higher precipitations on sandy soils of good permeability does not suggest negative effects. Nevertheless, reduced rainfall and higher temperatures could reduce forage production over the agricultural areas. An important aspect regarding pastures is relative to the fact that the increase of carbon dioxide concentrations according to the future scenarios would slightly increase the production of pastures and could reduce the digestibility and protein content of the pastures (Augustine et al. 2018).

The interactions are lower for the semi-intensive system and have no effect on intensive system because their production depends less on the growth of the pastures and can organize their production periods avoiding or minimizing exposure to higher temperatures.

Based on the analysis using GRAZE carried out for the Reconquista region, in the northeast of the province of Santa Fé, with cattle's genotype product of the cross-breeding of *Bos indicus* and *Bos taurus*, the combined action of higher temperatures with lower rainfall, increased the days with water stress in the pastures, between 97 and 148% according to the horizons and RCPs is considered. Hours with heat stress in animals grew between 0.9 and 5.9% for the same horizons and RCPs, while cold stress had a decreasing trend. Although it is not possible to define how much of the effect on the production of forage comes from the higher temperatures and how much is due to the lower rainfall, it can be assumed that there is a greater effect on forage production than on the body thermoregulation of the animal. (Argentina. Agricultura y

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