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Variation of temperatures, rains and winds, related to the altitude in an eco-tone between the Mountain Chaco and the Arid Chaco

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ABSTRACT

The work to determine the thermal inversion phenomenon was carried out on the western slope of Pocho Mountain, Córdoba, Argentina. Three meteorological boxes were installed there at 550 (LQ), 400 (JI), and 360 (EC) MASL. Although this phenomenon can occur throughout the year, it is more noticeable in autumn-winter. A high positive and significant correlation was found between altitude and mean absolute minimum temperature in May, June, July, and August ($r = 0.669$; $P < 0.05$).The average increase in the absolute minimum temperature between EC and LQ, during the four years studied for the months of May, June, July, and August, was 5.3; 4.8; 3.5, and 3.1°C, respectively; This covers an extension of 2.4 km long with a drop of 150 m. The information obtained here determined the frequent presence of the atmospheric phenomenon of thermal inversion in the foothills of Pocho Mountain, which opens the possibility of using a strip of at least 2,404 m wide for the production of crops susceptible to frost, as is the case of Jojoba, and forage species with a high protein content such as Leucaena and Moringa.

Key words: termal inversion. Sierra de Pocho, Arid Chaco, Mountain Chaco.

RESUMEN

Variación de las temperaturas, lluvias y vientos en relación con la altitud en un ecotono entre el Chaco Serrano y el Chaco Árido

El trabajo para determinar el fenómeno de la inversión térmica se llevó adelante en la ladera occidental de la Sierra de Pocho, Córdoba, Argentina. Allí se instalaron tres casillas meteorológicas a los 550 (LQ), 400 (JI) y 360 (EC) msnm. Si bien este fenómeno se puede presentar durante todo el año, es más notable en otoño-invierno. Se determinó una alta correlación positiva y significativa entre la altitud y la temperatura mínima absoluta media de mayo, junio, julio y agosto ($r = 0{,}669$; $P < 0{,}05$). El incremento medio de la temperatura mínima absoluta entre EC y LQ, durante los cuatro años estudiados fue 5,3; 4,8; 3,5 y 3,1 °C para los meses de mayo, junio, julio y agosto respectivamente. Esto abarca una extensión de 2,4 km de largo con un desnivel de 150 m. La información aquí obtenida determinó la presencia del fenómeno atmosférico de la inversión térmica en el piedemonte de la Sierra de Pocho, lo que abre la posibilidad de utilizar una franja de al menos 2.404 m de ancho para la producción de cultivos susceptibles a las heladas, como es el caso de la Jojoba, y especies forrajeras de alto contenido proteico como la Leucaena y la Moringa.

Palabras clave: inversión térmica, Sierra de Pocho, Chaco Árido, Chaco Serrano.

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INTRODUCTION

The South American Gran Chaco with an area of 114 million hectares is the second largest hardwood forest in the subcontinent, behind the Amazon Rainforest, representing a fifth of the Brazilian Amazon area. It is found covering tropical and subtropical latitudes, in the countries of Argentina, Paraguay, Bolivia, and Brazil, with percentages of 59, 23, 13, and 5, respectively (Naumann, 2006).

According to its rainfall regime, the South American Gran Chaco is divided into five subsystems, called Humid Chaco (1200-1400 mm), Sub-humid Chaco (750-1200 mm), Semiarid Chaco (500-750 mm), Arid Chaco (300-500 mm) and Mountain Chaco (500-900 mm). It is common to group the Arid and Semiarid Chaco under the name Dry Chaco. Precipitation decreases from east to west from 1400 mm to 300 mm. The Mountain Chaco, also called Mountain Chaco District or Mountain Chaco Park (Ragonese y Castiglioni, 1970; Cabrera, 1976), extends from north to south, from southern Bolivia to the center of Argentina, through the slopes of the Sub-Andean and Pampas Mountains interrupting the gradient of increasing aridity towards the Andes mountains range, occupying the lower slopes of hills and ravines (Naumann, 2006). Pampas Mountains are generally oriented from north to south, presenting a steep and short slope on the western face and a much smoother and longer slope on the eastern one.

In Pocho Mountains, province of Córdoba, the mountain forest is located between 500 m and 1400 m above sea level; it develops discontinuously and with different physiognomies due to differences in exposure, the heterogeneity of these environments and the alterations caused by human activities. The mountain forest is dominated by Molle (*Lithraea molleoides* (Vell.) Engl.) and Horco Quebracho (*Schinopsis haenkeana* Engl.), trees that are generally distributed as isolated individuals (Ragonese y Castiglioni, 1970).

The Mountain Chaco transforms to the west into the plain that makes up the Arid Chaco through an ecotone where herbaceous, shrubby, tree and cacti species from both Chaco subsystems intermingle. In the ecotone studied here, the appearance of specimens of Horco Quebracho was considered as a clear beginning of the Mountain Chaco to the east, and that of the Arid Chaco to the west, with the presence of specimens of Cachiyuyo (*Atriplex cordobensis* Gand. & Stuck.). This occurs at approximately 500 and 350 meters above sea level, for the eastern and western limits, respectively.

In this broad ecotone were: 1) trees and shrubs: Quebracho Blanco (*Aspidosperma quebracho-blanco* Schltdl.), Algarrobo Negro (*Prosopis flexuosa* DC.), Tintitaco (*Prosopis torquate* (Cav. ex Lag.) DC.), Mistol (*Ziziphus mistol* Griseb.), Brea (*Parkinsonia praecox* (Ruiz & Pav. ex Hook.) Hawkins), Lata (*Mimozyganthus carinatus* (Griseb.) Burkart), Abriboca (Maytenus spinosa (Griseb.) Lourteig & O´Donell), Jarilla (*Larrea divaricate* Cav.), Garabato macho (*Acacia furcatispina* Burkart); 2) grasses: *Trichloris crinita* (Lag.) Parodi, *Trichloris pluriflora* E. Fourn., *Aristida adscencionis* L., *Setaria* spp., *Chloris virgata* S.W., *Digitaria sp.* and *Gouinia paraguayensis* Kunt. Parodi; and 3) succulents: Ucle (*Cereus Validus* Haworth) and Tuna (*Opuntia sp.*).

The temperature inversion effect is a natural phenomenon that involves a change in the normal tendency of air to cool with altitude. The increase in temperature with altitude is a type of character that atmosphere acquires when the air temperature, instead of descending as we rise in height, as is normal, rises more and more. This occurs when the heat received by the ground by radiation during the day is lost rapidly at night, and the layers of air near it cool faster than the upper layers of air (Martino et al., 2016; UNAM, 2022).

Temperature is negatively correlated with altitude above sea level (Montgomery, 2006). The mean value of this variation is considered to be -1 °C/100m; it is not a constant value because it depends on the humidity content of the air, the time of year, altitude, etc. (González-Moreira, 2015). On certain occasions and for many reasons, instead of decreasing, an increase in temperature can occur as one goes up; this phenomenon is known as thermal inversion (Andrades-Rodríguez y Múñez-León, 2012). This commonly happens along a sloped surface like foothills. Here, the surface radiates heat back into space rapidly, cooling faster than the upper layers. As a result, the lower cold layers condense and become heavy. The sloping surface below causes them to drift to the bottom where the cold layer settles as a low-temperature zone while the upper layers are relatively warmer (U.S. Army Corps of Engineers, 1997; Kacharm *et al.*, 2015).

The phenomenon of thermal inversion has been reported on the slopes of the Pampa Mountains in the Provinces of San Juan (Dalmasso *et al.*, 2022) and Tucumán (Gutiérrez-Angonese, 2015). In a practical way, this phenomenon could be perceived in the mid-1970s when jojoba (*Simmondsia chinensis* Link. Schneider) was introduced in the foothills of the Pocho Mountain, in Las Oscuras, Córdoba, Argentina. This species is susceptible to frost, and an increase in plant damage was observed as one descended in MASL. The objective of this work was to determine on the western slope of Pocho Mountain, Córdoba, the effect of altitude above sea level, on temperatures, precipitation, and winds.

MATERIALS AND METHODS

The work was carried out at El Desafío farm, located on the western slope of the Pocho Mountain, Pocho, Córdoba, Argentina, belonging to the so-called Eastern Pampa Mountain. Three meteorological boxes were installed there on a descending gradient with measurements at 550 (31°37′50"S, 65°17′14"W), 400 (31°38′23"S, 65°18′36"W),and 360 (31°38′32"S, 61°19′40"W) meters above sea level, named La Quebrada (LQ), Jardín de Introducción (JI) and El Casco (EC), respectively. The distance between LQ and JI was 2404 m and between the latter and EC 1,649 m. The slope is 6.23% and 2.42% between the first two sites and between the second and third, respectively.

LQ was located at the limit of the slope that could be used in order to plant bushes or tree crops due to the abrupt increase in the slope to the east. EC was located to the west where it practically reaches minimal unevenness.

The temperature measurements were carried out in meteorological boxes built according to the following specifications: wooden structure in the form of a rectangle box, 85 cm side by 60 cm deep and 80 cm high; the roof had two wooden covers between which a small space allowed air to circulate freely. The double door was facing south, with the sides, including the door, in the form of shutters, painted in enameled white. They were raised to 1.25 m on a natural ground of herbaceous vegetation, maintained at a height of between 10 and 20 cm; said vegetation remained 20 m around the box, without obstacles, plants or constructions that could cast a shadow on the square at any time.

Daily temperature measurements were made with analog drum thermographs and AT 3000 model diagrams, with a roll of millimeter graph paper for seven days (Bauer Metrawatt Gmbh, Nuremberg, Germany).

Rainfall was measured in three type B rain gauges installed 1.5 m from the ground, according to the system of the Argentine Meteorological Service, Villa Dolores airport, Córdoba, Argentina (Ayerza (h), 1984a).

The force of the north wind was measured with an anemograph bowl with the determined values reproduced in a graph paper anemogram (Bauer Metrawatt Gmbh, Nuremberg, Germany), placed inside the weather box. The wind was classified as regular and strong. The first classification ranged from 31 to 50 km and the second from 51 to 80 km. The regular and strong wind classifications group together classes 4-5-6 and 7-8-9, from the Beaufort classification (Meteorological Office UK, 2022a), respectively. Only the north wind was measured, since it is the dominant one and the only one that, due to its strength, can produce changes in the landscape. Rainfall data was collected each day of occurrence(between 8 and 10 AM), temperatures every seven days, and wind speed every 30 days, transcribing data from thermograph and anemograph sheets for four years: 1983, 1984, 1985 y 1986.

The information was analyzed in 2022. Statistical determinations (means, standard deviations and correlations) were carried out through the program CoStat 6 (CoStat, 2005).

RESULTS AND DISCUSSION

Although the period of years studied (Table 1) cannot be considered sufficient to characterize the climate of a certain locality, it is sufficient to determine the differences at different altitudes in the same mountain range (García *et al.*, 2012; Joly and Richard, 2018; Espín-Sánchez *et al.*, 2018). It also serves to explain the variations observed in three tropical and subtropical exotic species implanted in 1978, Buffel Grass (*Cenchrus ciliaris* L.), Leucaena (*Leucaena leucocephala* (Lam.) de Wit) and Jojoba, cultivated in the same sites for at least 40 years (Ayerza (h), 1984b; 1990; 2020; 2022a; 2022b). The information available on these and other compared species, even during some of the years studied here, showed clear behaviors in response to climatic differences such as the extreme minimum temperatures determined there (Ayerza (h), 1990; 2020).

To be as rigorous as possible, thermal inversions should be studied from the equivalent potential of temperatures to take into account the effects of elevation, saturation, and changes in water status. Since most of the meteorological stations do not measure pressure or humidity, most of the works are based on temperature, as in the present study (Joly y Richard, 2018), considering it sufficient to determine the occurrence of this meteorological phenomenon.

In Tables 1, 2, 3, 4 and 5, the data obtained during the four years measured in the three meteorological cells and their means and standard deviations are found.

The site called LQ presented, as an average of the four years, the lowest values in the annual mean temperature with 3.7 and 8.9°C less than JI and EC, respectively. Likewise, the values of the Standard Deviations of the annual mean temperatures during the period studied at the LQ site showed a lower thermal variation throughout the year, compared to the other two (Table 2).

Table 1. Absolute minimum temperatures and mean minimum temperatures by site and year.
Tabla 1. Temperaturas mínimas absolutas y temperaturas mínimas medias por sitio y año.

Month	J	F	M	A	M	J	J	A	S	O	N	D	SD	Mean
Absolute minimum temperature (°C)														
LQ-83	12.7	15	12	13	-1	-1	1	4	3	7	12	16	6.36	7.81
LQ-84	18	13	12		1	1	1	1	4	6	10	7	5.59	6.75
LQ-85	10	14	8	6	5	1	-1	-1	4	6	10	10	4.71	6.00
LQ-86	10	14	10.70	10	2	0	3	4	3	6	10.70	11	4.54	7.03
Mean	12.68	14	10.68	9	1.75	0.25	1	2	3.50	6.25	10.68	11	5.00	6.75
SD	3.77	0.82	1.89	3.16	2.50	0.96	1.63	2.45	0.58	0.50	0.94	3.74		
JI-83	19	17	12	13	-3	-3	0	3	0	6	12	16	8.09	7.67
JI-84	13	17	10	5	-1	2	3	-3	4	9	7	11	5.87	6.42
JI-85	8	10	7	0	3	-2	-2	0	3	6	11	12	5.03	4.67
JI-86	10	16	10	10	-2	-4	2	3	3	6	11	14	6.26	6.58
Mean	12.50	15	9.75	7	-0.75	-1.75	0.75	0.75	2.5	6.75	10.25	13.25	5.89	6.33
SD	4.80	3.37	2.06	5.72	2.63	2.63	2.22	2.87	1.73	1.50	2.22	2.22		
EC-83	16	16	12	2	-4	-6	0	2	0	4	14	18	8.50	6.17
EC-84	19	18	10	4	-5	-3	-4	-5	4	7	7	9	8.32	5.08
EC-85	10	9	7	-3	-3	-6	-5	-4.50	0	7	10	11	6.82	2.71
EC-86	10	14	9	7	-2	-3	-1	3	2	7	10	12	5.73	5.67
Mean	13.75	14.25	9.50	2.50	-3.50	-4.50	-2.50	-1.13	1.50	6.25	10.25	12.50	7.02	4.91
SD	4.50	3.86	2.08	4.20	1.29	1.73	2.38	4.21	1.91	1.50	2.87	3.87		
Mean minimum temperature (°C)														
LQ-83	19.11	19	17.58	17.87	7.29	1.20	3.81	8.16	9.80	11.45	18.90	23.32	7.08	13.12
LQ-84	21.87	17.83	18.45	12.50	9.68	7.37	6.13	5.81	7.57	15.45	17.73	14.77	5.51	12.93
LQ-85	14.94	18.62	14.35	13.27	9.61	5.2	2.97	4.32	8.9	10.71	16.20	16.81	5.21	11.33
LQ-86	20.52	19.04	16.79	13.55	9.42	6.13	7.77	7.35	8.93	13.71	17.61	18.30	5.16	13.26
Mean	19.11	18.62	16.79	14.30	9	4.98	5.17	6.41	8.80	12.83	17.61	18.30	0.90	13
SD	3	0.56	1.76	2.42	1.15	2.67	2.19	1.70	0.92	2.16	1.11	3.65		
JI-83	22.16	21.32	17.48	18.83	8.48	0.27	3.29	10.45	9.37	12.84	19	22.77	5.52	13.86
JI-84	22.13	21.45	19.16	13.17	11.52	8.57	8.19	6.39	9.80	18.29	19.27	17.29	7.55	14.60
JI-85	12.74	18.57	14.71	11.63	10.1	4.87	3.19	5.23	9.17	12.74	18.33	18.33	5.61	11.63
JI-86	21.31	19.86	17.71	14.13	8.94	5.17	6.74	7.29	9.64	14.74	19.63	21.13	5.36	13.86
Mean	17.24	16.43	14.74	13.25	7.80	3.97	4.48	6.31	7.76	11.31	15.45	16.85	1.28	11.15
SD	4.58	1.36	1.86	3.10	1.36	3.41	2.51	2.24	0.28	2.59	0.55	2.52		
EC-83	20.71	20.64	18.26	15.70	7.58	-0.63	1.61	8.10	7.90	11.19	21.30	23.42	8.14	12.98
EC-84	23.61	22.55	19.13	11.23	8.39	5.77	4.42	2.29	7.73	17.52	17.33	17.45	7.34	13.12
EC-85	14.32	18.64	14.23	10.03	8.55	3.93	3.74	4.26	8.37	13.16	18.80	17.59	5.64	11.30
EC-86	21.52	19.07	14.94	13.77	10.19	5.13	6.10	7.03	9.89	14.39	18.20	20.23	5.69	13.37
Mean	20.04	20.23	16.64	12.68	8.68	3.55	3.97	5.42	8.47	14.07	18.91	19.67	0.94	12.69
SD	4.00	1.77	2.42	2.55	1.09	2.89	1.86	2.64	0.98	2.65	1.71	2.81		

The lowest absolute temperature (-6°C) was found at EC, the lowest site (360 MASL). Although there are no records available, to the west the absolute minimum temperatures should be even lower, since the slope continues up to a floor of 258 meters above sea level, located on the provincial border between the provinces of Córdoba and La Rioja, 22 km from EC, from where it begins to ascend again due to the folding of the Pampa Mountains of Chepes and Ulapes (Turner y de Alba, 1967; Google Earth, 2022).

Table 2. Absolute maximum temperatures, average maximum temperatures per site and year, and annual average for the period 1983-1986.
Tabla 2. Temperaturas máximas absolutas, temperaturas máximas medias por sitio y año, y media anual para el período 1983-1986.

Month	J	F	M	A	M	J	J	A	S	O	N	D	SD	Mean
Absolute maximum temperature (°C)														
LQ-83	40	39	38	34	27	24	23	25	29	33	46	42	7.73	33.33
LQ-84	39	32	35	30	29	29	29	28	29	42	39	36	4.91	33.08
LQ-85	37	40	39	30	27	27	21	26	27	31	37	37	6.20	31.58
LQ-86	44	42	37	33	30	24	22	29	35	38	41	40	7.12	34.58
Mean	40	38.25	37.25	31.75	28.25	26	23.75	27	30	36	40.75	38.75	6.03	33.15
SD	2.94	4.35	1.71	2.06	1.50	2.45	3.59	1.83	3.46	4.97	3.86	2.75		
JI-83	41	39	40	35	27	25	27	29	31	38	47	45	7.44	35.33
JI-84	39	38	39	32	30	29	29	31	34	45	42	39	5.43	35.58
JI-85	33	37	45	31	30	29	26	26	30	40	42	40	6.47	34.08
JI-86	47	37	41	37	37	24	26	30	39	38	47	47	7.73	37.50
Mean	40	37.75	41.25	33.75	31	26.75	27	29	33.5	40.25	44.5	42.75	6.27	35.63
SD	5.77	0.96	2.63	2.75	4.24	2.63	1.41	2.16	4.04	3.30	2.89	3.86		
EC-83	48	42	40	39	39	29	24	26	32	39	46	46	8.01	37.50
EC-84	40	39	38	34	30	29	28	29	34	44	40	40	5.45	35.42
EC-85	37	38	42	30	29	29	28	27	34	45	41	39	6.22	34.92
EC-86	46	45	35	36	32	27	26	33	39	38	46	48	7.48	37.58
Mean	42.75	41.00	38.75	34.75	32.50	28.50	26.50	28.75	34.75	41.50	43.25	43.25	6.23	36.35
SD	3.70	2.59	2.29	4.08	1.70	2.53	1.20	0.95	1.07	1.62	1.49	3.73		
Average maximum temperature (°C)														
LQ-83	32.43	29.14	31.48	25.10	22.03	18.27	18.06	20.06	21.5	29.81	30.37	33.65	5.79	25.99
LQ-84	32.29	28.48	26.45	24.03	23.39	16.43	18.94	21.61	25.6	31.61	32.63	27.06	5.16	25.71
LQ-85	30.65	30.73	29.96	24.73	22.65	18.40	16.03	20.03	22.63	26.26	27.73	30.41	5.11	25.02
LQ-86	34.34	34.57	29.3	25.67	21.61	19.03	17.61	19.97	23.5	28.9	30.24	30.37	5.87	26.26
Mean	32.43	30.73	29.30	24.88	22.42	18.03	17.66	20.42	23.31	29.15	30.24	30.37	5.28	25.74
SD	1.51	2.73	2.11	0.69	0.78	1.12	1.22	0.80	1.73	2.23	2.00	2.69		
JI-83	37.87	31.36	34.29	26.93	23	18.5	20.42	21.97	22.53	30.94	31.97	35.55	6.54	26.30
JI-84	27.68	31.54	31.23	24.17	23.55	21.8	18.06	21.39	24.8	28.97	30.47	33	4.76	24.72
JI-85	34.03	32.31	29.03	25.07	25.94	20.30	21.13	24	27.63	33.9	35.07	29.74	5.04	26.40
JI-86	36.73	35.11	31.52	28.73	22.61	19.23	20.10	20.81	24.61	30.48	35.10	37.94	6.89	26.91
Mean	34.08	32.58	31.52	26.23	23.78	19.96	19.93	22.04	24.89	31.07	33.15	34.06	5.55	27.77
SD	4.56	1.74	2.16	2.03	1.49	1.43	1.32	1.39	2.09	2.06	2.31	3.51		
EC-83	39.23	37.75	34.35	32.9	27.26	15.93	19.84	21.32	25.93	30.29	32.37	36.13	7.46	29.44
EC-84	34.84	33.41	28.97	25.27	24.58	17.57	21.84	22.97	27.4	32.77	33.38	29.32	5.40	27.69
EC-85	30.35	31.61	31.16	24.07	23.48	21.33	18.97	21.35	24.97	28.87	31.10	32	4.74	26.61
EC-86	36.27	34.71	30.32	29.73	23.87	20.57	20.39	23	25.32	30.87	34.6	37.42	6.14	28.92
Mean	35.17	34.37	31.20	27.99	24.80	18.85	20.26	22.16	25.91	30.70	32.86	33.72	5.70	28.17
SD	3.70	2.59	2.29	4.08	1.70	2.53	1.20	0.95	1.07	1.62	1.49	3.73		
Annual average temperature for the period (°C) 1983-1986														
LQ	20.32	19.30	18.31	15.55	13.64	10.75	10.55	12.24	14.12	17.84	18.93	19.07	3.53	15.89
JI	25.66	24.50	23.13	19.74	15.79	11.97	12.20	14.18	16.32	21.19	24.30	25.45	5.22	19.54
EC	32.14	30.04	26.85	24.26	21.35	16.82	16.30	17.89	22.32	27.95	30.73	31.74	5.88	24.86
Mean	26.04	24.61	22.76	19.85	16.92	13.18	13.02	14.77	17.59	22.32	24.65	25.42		
SD	5.92	5.37	4.28	4.35	3.98	3.21	2.96	2.87	4.24	5.15	5.91	6.34	4.51	20.09

The necessary conditions for the occurrence of the thermal inversion phenomenon include: long nights, so that outgoing radiation is greater than incoming radiation, clear skies, which allow unobstructed escape of radiation, and calm, steady winds, so that there is no vertical mixing at lower levels (National Weather Service, 2022). In general, their presence is effective mainly between 1 and 6 AM and secondly between 6 and 12 PM (Hernández *et al.*, 1997). The thermal inversion stratum disappears during the first hours of the morning with the appearance of the sun and the consequent warming of the earth (Whiteman *et al.*, 2008).

The greater occurrence of the phenomenon at this time has a positive effect during the frost period, since they occur close to the time that the minimum daily temperature occurs periodically, raising it, which favors agriculture in the foothill area dedicated to the cultivation of fruits and vegetables sensitive to frost (Hernández *et al.*, 1997).

Although this phenomenon can occur throughout the year, it is more noticeable in autumn-winter (Nols-Suarez, 2014; Meteorological Office UK, 2022b), as we can see in Table 1, with the values of the average extreme minimum temperatures during the months of May, June, July and August, with a difference of more than 2.5 and 5.3; 2 and 4.8; 0.3 and 3.5;1.3 and 3.1°C for the differences between LQ with those of the JI and those of EC, respectively. A specific example in the same year is given by the differences obtained in LQ, with respect to the JI and EC, which was 1 and 4 degrees Celsius, respectively, for the month of July, 1985 (Table 1).

The greatest frequency of the phenomenon was recorded during the dry season, when days with clear skies and calm atmosphere prevail, added to the decrease in sunshine, water vapor and cloudiness that intensify the cooling of the underlying air in the mountainous area.

The practical disappearance of the thermal inversion from October to November would be due to the greater advection of warm and humid subtropical air, characteristic of the rainy season, as has been reported for Guadalajara, Mexico (Hernández *et al.*, 1997).

The reason for the greater temperature inversion in the months of May and June does not appear with the information available. However, it could be influenced by various joint factors such as the increase in the number of days with rain, the strong north wind in July and August (Table 2) since these interfere causing mixtures in the air layers, and the shorter duration of the night in these months compared to July and August, which are up to 25 and 30 minutes reduction for July and 80 and 85 minutes for August, compared to the months of May and June, respectively; the longer the night the greater the probability that the outgoing radiation will be greater than the incoming radiation (Meteorological Office UK, 2022a). These three characteristics have been reported as basic components in the formation and intensity of thermal inversions (Andrades-Rodríguez y Múñez-León, 2012; National Weather Service, 2022).

The decrease in the intensity of the thermal inversion between sites decreases with the decrease in altitude, as has been determined in the Sierra of San Javier, Tucumán, that is, on the slope, at a greater distance from the mountain, less thermal increase. This is due to the air descending faster as a result of strong cooling, causing an increase in turbulence that determines the removal of cold stratified layers, causing the largest increases that are not observed to the west due to the weakening of slope (Hernández *et al.*, 1997).

In the months of May and June of 1983 and July and August of 1985, LQ received frosts (-1°C); temperatures in the same months and years were -3 and -3°C, and -2 and 0°C for the JI site, and -4 and -6°C, and -5 and -4.5°C for the EC site (Table 1), respectively.Another notable comparative data is the number of months with frost in the 1983-1986 period, which was significantly different between sites with 4, 8 and 14 for LQ, JI and EC, respectively; while LQ gets frost only 50% of the years, the other two sites have frost every year. Even EC was the only site to receive frost (-3°C) in April, 1985, compared to an absolute minimum of 6°C at LQ.

The mean absolute minimums of the three sites begin to separate in March, reaching their maximum divergence during May and June, coming together again in September (Figure 1).This winter behavior goes hand in hand with a marked decrease in extreme minimum temperatures that deepens with the decrease in masl (Table 1). In agreement, a high positive and significant correlation was determined between altitude and mean absolute minimum temperature for the months of May, June, July and August ($r = 0.669$; $P < 0.05$, Figure 2). The average increase in the absolute minimum temperature between EC and LQ, during the four years studied for the months of May, June, July and August, was 5.3 – 4.8 – 3.5 and 3.1°C, respectively;these values imply a rise of 0.027 - 0.025 - 0.18 and 0.016°C/m of elevation, respectively. In general, in the foothills the thermal inversion presents a temperature increase of 0.01°C/m, having been determined in the Pampa Mountains up to maximums of 0.087°C, as was reported for the San Javier Mountain, province of Tucuman (Hernández *et al.*, 1997).

Comparing month by month the extreme sites LQ and EC during the winter presence of the thermal inversion, EC presented higher absolute maximum temperatures and lower absolute minimum extreme temperatures than LQ (Figure 1). This characteristic has also been determined when this phenomenon occurs, in numerous localities such as Madrid and Murcia (Spain), Tucson (U.S.A.), Jura (France), La Rinconada (Ecuador) and Guadalajara (Mexico) (U.S. Army Corps of Engineers, 1997; García *et al.*, 2012; Espín-Sánchez, 2014; Joly and Richard, 2018; Ayerza (h), 2019; Gaite-Fox, 2021).

These values demonstrate the existence of the phenomenon of autumn-winter thermal inversion and mark on the slope a limit below 400 masl, practically impassable for the cropping of species such as jojoba, which suffers total losses in open flowers with temperatures below -1°C and withstanding closed flowers down to -3°C (Ayerza (h), 1990).

These temperatures occur in an extension of land with a drop of 150 m and 2.4 km long; multiplying this area by an extension of 430 km, which is the length of the Pampa Mountain range in Cordoba (Krapovickas y Tauber, 2016), the approximate area is 103,200 hectares.

It has been shown that the phenomenon of thermal inversion occurs every year, with small variations regarding the height and temperature limits, which makes the dimension of the surface area covered by the phenomenon repeatable over time, and therefore reliable in controlling the intensity of frost (Nols-Suárez, 2014; Czarnecka and Nidzgorska-Lencewicz, 2017).

As an antecedent of this potential, in the Pampa Mountains of the Province of Tucumán, between San Miguel de Tucumán and La Cocha, temperatures have been determined that suggest that this phenomenon of thermal inversion is repeated in the 130 km of foothills between these two locations (Hernández *et al.*, 1997).

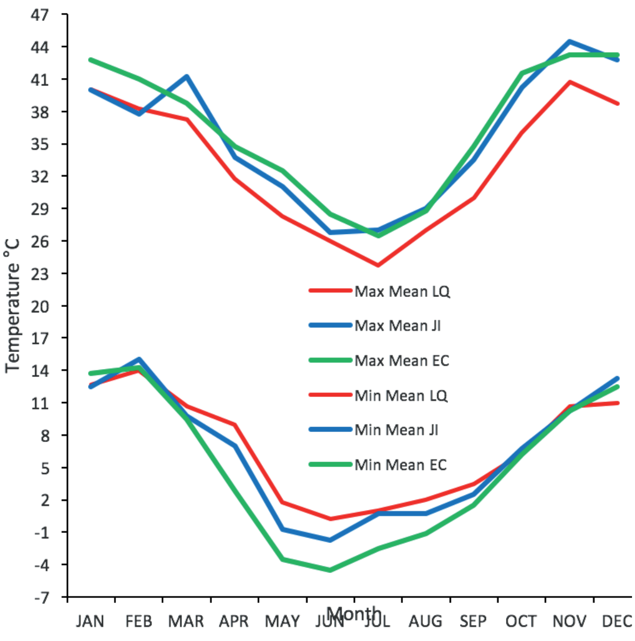

Figure 1. Comparative graph of the mean absolute maximum and minimum temperatures of the three sites during the 1983-1986 period.
Figura 1. Gráfico comparativo de las temperaturas máximas y mínimas absolutas medias de los tres sitios durante el período 1983-1986.

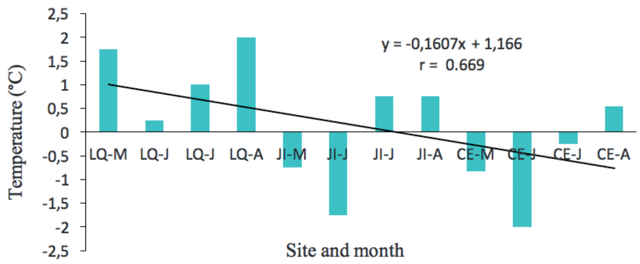

Figure 2. Correlation between altitude and mean absolute minimum temperature for the months of May, June, July and August.
Figura 2. Correlación entre altitud y temperatura mínima absoluta media para los meses de mayo, junio, julio y agosto.

The presence of the thermal inversion phenomenon has allowed the production of jojoba seeds regularly since 1976 at the LQ site, irregularly at the JI site and null at the EC site. Even having been abandoned from all cultivation in the last 30 years, productive plants of this species still grow in the first two sites, while in the EC site they had disappeared only four years after their implantation, attributed to the annual presence of extreme minimums of between -5 and -6°C (Ayerza (h), 2020).

The presence of the thermal inversion phenomenon in the foothills of the Pocho Mountain allows the cultivation of species that are very intolerant to frost, and cannot prosper with the minimum temperatures present in the valley. In addition to Jojoba (high performance liquid wax), other species such as Moringa (*Moringa oleifera* Lam.) producing an oil of high cosmetic value, and foliage for human and animal food), and the Leucaena, producer of fodder of high protein value, have been successfully tested in these foothills (Ayerza (h), 2011). The last two species allow the production of a high-protein forage that enables the supplementation of cattle raised in the plain, which graze foliage that in winter is limiting for its development due to its low protein content (Ayerza (h) 2017; 2020; 2022b).

The values of the standard deviations of the mean annual temperatures for the period 1983-1986 show a smaller variation in the temperatures of LQ than in those of JI and EC (Table 3), demonstrating a smaller comparative dispersion of the thermal values.

Total rainfall and its distribution over the years were very similar among the three sites (Table 4) studied and are consistent with those obtained in the Chancani Forest Reserve, located 25 km to the north, also on the foothills of this Mountain, with an average of 512 mm (Iglesias *et al.*, 2010).However, the means of the period studied in this trial were higher than the mean of 350 mm obtained between 1966 and 1990, with minimums of 130 and maximums of 734 mm measured at JI (Ayerza (h), 2022b).

In Table 5 we can see the north wind speed and the number of days it blew strongly and regularly, during the period 1983-1986. The north wind is a constant in the Arid Chaco (Morlans y Guichon, 1995; Konverski y de la Orden, 2016), so here we only include those days when they cause damage to the landscape and markedly hinder agricultural activities. The maximum mean annual frequency of strong and regular winds was 38 days for EC and 28 for LQ; 1986 was the year with the highest frequency of days with strong wind with 53, 50 and 28 days for LQ, JI and EC, respectively. The notable difference between LQ and the other two sites may be explained by the fact that the first is located in a 300 m-wide ravine, so it is more protected than the other two, located on the slope exposed to direct wind. The month of June was the only one that did not present days with strong or regular wind in any of the years studied, and October > November > January > December, the months that presented the highest average frequency. Although the values of the Standard Deviations did not

Table 3. Monthly rainfall and days with rain by site and year.
Tabla 3. Precipitación mensual y días con lluvia por sitio y año.

Month	J	F	M	A	M	J	J	A	S	O	N	D	SD	Mean
Rainfall (mm)														
LQ-83	398	0	17	26	0	0	0	31	29	65	76	85	727	115.63
LQ-84	197	106	63	6	0	0	0	0	48	2	20	212	654	62.45
LQ-85	100	0	62	11	0	0	110	36	0	7	82	96	504	43.59
LQ-86	146	165	0	0	0	0	30	0	0	30	0	0	371	61.50
Mean	110.80	67.80	35.50	10.80	0.0	0.0	35	16.80	19.30	26	44.50	98.30	564	59.15
SD	83.79	81.86	31.94	11.12	0.00	0.00	51.96	19.45	23.54	28.72	40.74	87.13	158.66	
JI-83	322	51	6	16	0	0	13	26	26	54	62	88	664	88.35
JI-84	189	104	59	6	0	0	0	0	44	2	25	218	647	77.02
JI-85	104	72	54	8	0	0	107	27	0	10	85	62	529	41.57
JI-86	135	168	0	0	0	0	29	0	27	32	9	62	462	56.55
Mean	187.50	98.80	29.80	7.50	0.0	0.0	37.30	13.30	24.30	24.50	45.30	107.50	576	56.09
SD	96.30	51.05	31.05	6.61	0.00	0.00	47.99	15.31	18.15	23.40	34.57	74.68	96.59	
EC-83	369	46	11	19	0	14	14	29	28	57	65	82	734	100.04
EC-84	190	112	52	5	0	0	0	0	44	2	21	216	642	77.50
EC-85	105	68	46	10	0	0	107	0	0	12	102	64	514	44.66
EC-86	132	168	10	0	0	0	31	0	25	35	9	63	473	55.57
Mean	199	98.50	29.80	8.50	0.0	3.50	38	7.30	24.30	26.50	49.30	106.30	591	58.54
SD	118.75	53.85	22.37	8.10	0.0	7.00	47.71	14.50	18.19	24.58	42.62	73.69	119.59	
Dayswith rain														
LQ-83	9	0	6	3	0	0	0	3	3	3	4	5	36	2.80
LQ-84	6	2	9	1	0	0	0	0	3	2	1	8	32	3.23
LQ-85	8	0	5	1	0	0	5	2	0	2	3	5	31	2.64
LQ-86	4	7	0	0	0	0	1	0	0	2	0	0	14	2.21
Mean	4.50	2.25	5	1.25	0	0	1.50	1.25	1.50	2.25	2	4.59	28.25	2.05
SD	3.34	3.58	3.27	1.06	0.00	1.75	1.85	1.51	1.25	1.25	2.82	12.89	9.74	
JI-83	9	4	2	1	0	0	1	3	3	2	4	5	34	2.52
JI-84	5	2	9	1	0	0	0	0	44	2	25	218	30	3.15
JI-85	8	3	5	1	0	0	5	2	0	2	3	6	35	2.61
JI-86	4	8	0	0	0	0	1	0	1	2	2	3	21	2.38
Mean	6.50	4.25	4	0.75	0	0	1.75	1.25	1.50	2	2.50	5.50	30	2.12
SD	2.62	3.09	3.11	0.52	0.00	1.73	1.77	1.30	0.89	0.89	2.27	13.81	6.38	
EC-83	9	4	2	1	0	1	1	3	3	2	4	5	35	2.43
EC-84	5	2	5	1	0	0	0	0	2	2	1	8	26	2.55
EC-85	8	3	5	1	0	0	5	0	0	2	3	6	33	2.73
EC-86	5	7	1	0	0	0	1	0	1	2	2	3	22	2.21
Mean	6.80	4	3.30	0.80	0.0	0.30	1.80	0.80	1.50	2	2.50	5.50	29	2.11
SD	2.06	2.16	2.06	0.50	0.00	0.50	2.22	1.50	1.29	0.00	1.29	2.08	6.06	

Table 4. Average rainfall and average rainy days, by month of the period 1983-1986.
Tabla 4. Precipitación promedio y días de lluvia promedio, por mes del período 1983-1986.

Month	J	F	M	A	M	J	J	A	S	O	N	D	SD	Mean
Rainfall (mm)														
LQ	210.30	67.80	35.50	10.80	0.0	0.0	35	16.80	19.30	26	44.50	98.30	564	59.15
JI	187.50	98.80	29.80	7.50	0.0	0.0	37.30	13.30	24.30	24.50	45.30	107.50	575.50	55.44
EC	199.20	98.50	29.80	8,50	0.0	3.50	38	7.30	24.30	26.50	49.30	106.30	591	57.06
SD	11.40	17.80	3.30	1.70	0.0	2	1.60	4.80	2.90	1	2.60	5	13.50	1.90
Dayswith rain														
LQ	6.75	2.25	5	1.25	0	0	1.50	1.25	1.50	2.25	2	4.50	28.30	2.05
JI	6.50	4.25	4	0.75	0	0	1.75	1.25	1.50	2	2.50	5.50	30	2.12
EC	6.75	4	3.25	0.75	0	0	1.75	0.75	1.50	2	2.50	5.50	29	2.11
SD	0.14	1.09	0.88	0.29	0.00	0.00	0.14	0.29	0.00	0.14	0.29	0.58	0.85	0.04

show a great difference, they did how less variability in the frequency of the winds in the LQ site, compared to the other two, presenting the greatest variability in the ECsite. Here too, the reason for this difference must have been in the physical protection of air circulation in the LQ site.

Table 5. Strong and regular north wind speed by site and year.
Tabla 5: Velocidad del viento norte fuerte y regular por sitio y año.

Month	J	F	M	A	M	J	J	A	S	O	N	D	SD	Mean
Number of days with strong north wind (51-80 km/hour)														
LQ-83	0	0	0	7	0	0	0	0	2	4	0	5	18	2.47
LQ-84	3	0	0	0	0	0	1	3	3	14	7	0	31	4.19
LQ-85	0	0	0	0	2	0	0	0	2	8	8	0	20	3.06
LQ-86	10	0	0	1	0	0	5	5	0	7	0	0	28	3.50
Mean	3.30	0.0	0.0	2	0.50	0.0	1.50	2	1.80	8.30	3.80	1.30	24.30	2.33
SD	4.72	0.00	0.00	3.37	1.00	0.00	2.38	2.45	1.26	4.19	4.35	2.50	6.24	
JI-83	1	0	7	7	0	0	0	0	2	4	0	5	26	2.82
JI-84	3	0	0	0	1	0	1	3	3	14	7	0	32	4.14
JI-85	6	4	0	0	1	0	0	0	2	8	8	0	29	3.23
JI-86	11	0	0	1	0	0	5	5	0	7	15	6	50	4.99
Mean	5.25	1	1.75	2	0.50	0	1.50	2	1.75	8.25	7.5	2.75	34.3	2.69
SD	2.52	2.31	4.04	4.04	0.58	0.00	0.58	1.73	0.58	5.03	4.36	2.89	10.78	
EC-83	1	0	0	7	0	0	0	0	2	3	0	5	18	2.35
EC-84	3	0	0	0	1	0	1	3	3	14	9	0	34	4.37
EC-85	6	4	0	0	1	0	0	0	2	8	8	0	29	3.23
EC-86	10	0	4	1	0	0	5	4	0	7	16	6	53	4.91
Mean	5	1	1	2	1	0	2	2	2	8	8	3	33.5	2.79
SD	3.92	2	2	3.37	0.58	0.00	2.38	2.06	1.26	4.55	6.55	3.20	14.62	
Number of days per site with average strong north wind 1983-1986														
LQ	3.3	0	0	2	0.5	0	1.50	2	1.80	8.30	3.80	1.30	24.30	2.33
JI	5.25	1	1.75	2	0.50	0	1.50	2	1.75	8.25	7.50	2.75	34.30	2.69
EC	5	1	1	2	1	0	2	2	2	8	8	3	33.50	2.79
SD	1.06	0.58	0.88	0.00	0.29	0.00	0.29	0.00	0.13	0.16	2.29	0.92	5.56	
Number of days with regular north wind (31-50 km/hour)														
LQ-83	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LQ-84	0	0	0	0	0	0	0	0	0	0	0	4	4	0
LQ-85	0	0	3	7	0	0	0	0	0	0	0	0	10	2.12
LQ-86	1	0	0	0	0	0	0	0	0	0	0	0	1	0.29
Mean	0.30	0.0	0.80	1.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	15	2.41
SD	0.50	0	1.50	3.50	0	0	0	0	0	0	0	2	4.50	
JI-83	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JI-84	0	0	0	0	0	0	0	0	0	0	0	4	4	1.15
JI-85	0	0	5	7	1	0	0	0	0	0	0	0	13	2.35
JI-86	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean	0.0	0.0	1.30	1.80	0.30	0.0	0.0	0.0	0.0	0.0	0.0	1	17	0.62
SD	0	0	2.50	3.50	0.50	0	0	0	0	0	0	2	6.13	
EC-83	0	0	0	0	0	0	0	0	0	0	0	0	0	0.98
EC-84	0	0	0	0	0	0	0	0	0	0	0	4	4	0.87
EC-85	0	0	5	7	1	0	0	0	0	0	0	0	13	0.86
EC-86	1	0	0	0	0	0	0	0	0	0	0	0	1	0.40
Mean	0.30	0.0	1.30	1.80	0.30	0.0	0.0	0.0	0.0	0.0	0.0	1	18	0.61
SD	0.50	0	2.50	3.50	0.50	0	0	0	0	0	0	2	5.92	
Average number of days per site with regular north wind 1983-1986													Media	
LQ	0.25	0	0.75	1.75	0	0	0	0	0	0	0	1	3.75	0.57
JI	0	0	1.25	1.75	0.25	0	0	0	0	0	0	1	4.25	0.62
EC	0.25	0	1.25	1.75	0.25	0	0	0	0	0	0	1	4.50	0.61
SD		0.00	0.29	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	

CONCLUSIONS

The information obtained determined the presence of the atmospheric phenomenon of thermal inversion in the foothills of the Pocho Mountain. Which opens the possibility of using a strip of at least 2404 m wide to produce crops susceptible to frost, such as Jojoba, and forage species with high protein content such as Leucaena and Moringa.

Although the period studied showed the presence of the thermal inversion phenomenon in all the winters analyzed, and the behavior of the jojoba plants in the three sites over 40 years suggests so, it would be necessary to study the frequency of this atmospheric phenomenon during periods of longer time and in a greater number of sites through the Pampas Mountains range of Córdoba, in order to validate the productive potential of these foothills.

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