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Time series (ARIMA) as a tool to predict the temperature-humidity index in the dairy region of the northern desert of Mexico

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The environment in which an animal is situated can have a profound impact on its health, welfare, and productivity. This phenomenon is particularly evident in the case of dairy cattle. In order to quantify the impact of climatic conditions on dairy cattle, the Temperature-Humidity Index (THI) is employed as a metric. This indicator enables the practical estimation of the stress imposed on cattle by ambient temperature and humidity. A SARIMA model was estimated using daily data from the maximum daily THI of four years (2016-2019) of the Comarca Lagunera, an arid region of central-northern Mexico. The resulting model indicated that the THI of any given day in the area can be calculated based on the THI values of the previous four days. Furthermore, the data demonstrate an annual increase in the number of days the THI indicates a risk of heat stress. It is essential to continue building predictive models to develop effective strategies to mitigate the adverse effects of heat stress in dairy cattle (and other species) in the region.

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ABSTRACT

The environment in which an animal is situated can have a profound impact on its health, welfare, and productivity. This phenomenon is particularly evident in the case of dairy cattle. In order to quantify the impact of climatic conditions on dairy cattle, the Temperature-Humidity Index (THI) is employed as a metric. This indicator enables the practical estimation of the stress imposed on cattle by ambient temperature and humidity. A SARIMA model was estimated using daily data from the maximum daily THI of four years (2016-2019) of the Comarca Lagunera, an arid region of central-northern Mexico. The resulting model indicated that the THI of any given day in the area can be calculated based on the THI values of the previous four days. Furthermore, the data demonstrate an annual increase in the number of days the THI indicates a risk of heat stress. It is essential to continue building predictive models to develop effective strategies to mitigate the adverse effects of heat stress in dairy cattle (and other species) in the region.

INTRODUCTION

The negative impact of heat stress (HS) on livestock productivity has been well documented in the literature. Among others, the studies by Amundson et al. (2006), Armstrong (1994), Salem and Bouraoui (2009), Gantner et al. (2011), Hernández et al. (2011), and Kadzere et al. (2002) have all highlighted the detrimental effects of HS on animal thermoregulation and feed intake, fertility, and milk production. High-yielding animals are particularly susceptible to HS due to their elevated thermogenesis, which is a consequence of their heightened metabolic activity (Bernabucci et al. 2014; St-Pierre, Cobanov, and Schnitkey 2003). As dairy cows are primarily selected for their milk production, they are more susceptible to caloric stress, which has been demonstrated to significantly impair their fertility (Sammad et al. 2020). Furthermore, it has been demonstrated that in dairy cows that increase their milk production from 35 to 45 kg/d, the temperature threshold for HS can be lowered by 5 ºC. This indicates that higher milking cows are susceptible to HS at lower temperatures (Armstrong 1994). Consequently, the dairy industry incurs economic losses due to heat stress. In the United States, the financial impact of heat stress is estimated to range from 897 to 1.5 billion dollars annually (St-Pierre, Cobanov, and Schnitkey 2003).

A variety of bioclimatic indices have been utilized as a means of predicting the HS and its impact on dairy cattle. Of these indices, the Temperature-Humidity Index (THI) is the most utilized and practical. Its origins can be traced back to studies conducted in the 1940s. Moreover, it has been a valuable indicator of heat stress in dairy cattle since the 1960s (Vasseur et al. 2012). Since that time, the THI has been employed to assess the productive and reproductive response as a function of climate differences (Hahn, Mader, and Eigenberg 2003; Ravagnolo, Misztal, and Hoogenboom 2000; Silva, Morais, and Guilhermino 2007; Tolkamp et al. 2010). The THI is a practical bioclimatic marker that reflects the sum of external forces acting on animals (temperature and humidity) and their impact on body temperature homeostasis (Silva, Morais, and Guilhermino 2007). The THI is calculated using a variety of formulas developed from research that measure dry bulb, wet bulb, dew point temperatures, and relative humidity of the air (Sejian et al. 2013).

As previously proposed by Jeff E. (Houlahan et al. 2017), the objective of scientific inquiry is to gain an understanding of the natural world. The capacity to make predictions is the sole means of substantiating scientific comprehension, thereby establishing it as a foundational tenet of all scientific disciplines. In the modern era, prediction fulfills two vital functions. Firstly, prediction serves as a test of scientific understanding, thereby conferring authority and legitimacy upon it. Secondly, prediction may also function as a potential guide for decision-making (Sarewitz and Pielke Jr 1999).

In the Comarca Lagunera, situated in the northern arid region of Mexico, HS conditions are present throughout the year (305 d), exerting a detrimental impact on milk production, milk composition, cow comfort, and the ratio of milking cows to nonmilking cows. Furthermore, these conditions have the potential to impose an economic burden at the farm, regional, and societal levels (Rodriguez-Venegas et al. 2023). Mathematical models are employed by scientists to predict the potential consequences of natural phenomena, with the objective of developing strategies to mitigate their adverse effects. Among the aforementioned tools, the following may be identified: A time series can be defined as a collection of observations made sequentially over time, in a broad sense, and can be used to describe a variety of data sets. A time series can be defined as a specific type of stochastic process. The last decades have shown great progress in the technique and scope of the use of models in the biological sciences, however, in the area of farm animal welfare the variety, type, and complexity of the models used have not advanced at the same pace, despite the fact that they could have a great scope in this field of research (Collins and Part 2013). The present study will focus on time series exhibiting behavior consistent with the laws of probability, as opposed to deterministic series. In the field of dairy production by cows, time series analysis has been applied in several areas, including the modeling of diseases such as estrus (De Mol et al. 1999), the quantification of the effect of temperature on mortality in dairy cows (Morignat et al. 2015), the increase in production due to dietary changes (Kerr, Cowan, and Chaseling 1991), the demand for dairy products (Heien and Wessells 1988), and methane and CO_2 production (Lee et al. 2017). It is evident that the applications of this methodology to explain and predict the phenomenology in agricultural issues are numerous and diverse. This enables the implementation of preventative measures in a timely manner, thereby preventing any adverse effects on the health, comfort, and productivity of cows. For this reason, this article examines the predictive capacity of the THI in relation to potential HS events in the Comarca Lagunera, employing the time series method.

MATERIALS AND METHODS

The climate data from the Comarca Lagunera (102°22', 104°47' WL; 24°22', 26°23' NL, at 1139 m) were the subject of this study. This arid region of northern Mexico accounts for 21 % of the national dairy cow inventory and presents environmental conditions that present a significant challenge to Holstein cattle on dairy farms. These conditions include an average annual precipitation of 200 mm, extreme ambient temperatures that can range from -5 ºC in winter to 41.5 ºC in summer, and high solar radiation.

Ambient temperature (in degrees Celsius) and relative humidity (in percent) data were obtained to calculate daily THI using the DiGiTH™ application (DiGiTH Technologies, Mexico), from five representative geographical points (GPs), according to the process described in a previous study (Rodriguez-Venegas et al. 2022) (Rodriguez-Venegas et al., 2022). The geographical points (GPs) were as follows: The initial geographical point (GP1) is situated at 25.5° West Longitude (WL) and 103.25° North Latitude (NL). The second geographical point (GP2) is located at 25°61' North Latitude (NL) and 103°55' West Longitude (WL). The third geographical point (GP3) is situated at 25°90' NL and 103°39' WL. The fourth geographical point (GP4) is situated at 25°51' North Latitude and 103°60' West Longitude. The fifth geographical point (GP5) is located at 25°40’ NL and 103°31’ WL. The data set under consideration spanned the period from 2016 to 2019.

ARIMA model forecast groundwater level.

Box and Jenkins (Box et al. 2016), for a given time series, forecasted observation is calculated by Equation 1.

$$Y_t = Y_1 + Y_2 + Y_3 + \cdots + Y_t \tag{1}$$

In Equation 1, Y is the observations in the time of t.

If P is equal to 1, this equation converts into Equation 2, similar to Patle et al. (2015).

When,

$$P > 1; Y_t = c + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + e_t \tag{2}$$

In the study by Patle et al. (2015), the two constants c and ϕ_1 are employed to address the random error in t, while e_t is utilized to consider prior errors in a manner analogous to that described by Gibrilla, Anornu, and Adomako (2018).

$$Y_t = c + e_t - \phi_1 e_{t-1} - \phi_2 e_{t-2} - \cdots - \phi_q e_{t-q} \tag{3}$$

Sen’s estimator.

In general, the slope is employed for the evaluation of straight patterns through the processing of least squares estimation via linear regression. The slope estimation formula, as proposed by Sen (1968), is presented in Equation 4.

$$Q = \frac{Y_{i'} - Y_i}{i' - i} \tag{4}$$

where,

Q is an estimated slope.

$Y_{i'}$ is the sum of the values at times i' and i, where i' is greater than i.

Sen’s judge of the slope in the middle of N’s ups of Q.

Mann-Kendall Trend Test.

The Mann-Kendall test is a nonparametric method employed for the analysis of trends in time series data (Kendall 1948). The principal advantage of the Mann-Kendall test is that it does not require the prior specification of a statistical distribution, which is a prerequisite of parametric methods. The null hypothesis (H_0) of the Mann-Kendall test is that there is no trend or serial correlation among the population under analysis. In contrast, the alternative hypothesis (H_1) postulates the existence of an increasing or decreasing monotonic trend.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{5}$$

where the Mann–Kendall statistic is S and sign is the signum function. Sign $(x_j - x_i)$ calculated from Equation 6 as presented by Anand et al. (2020).

$$sign(x_j - x_i) = \begin{cases} +1 \text{ if } (x_j - x_i) > 0, \\ 0 \text{ if } (x_j - x_i) = 0, \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \tag{6}$$

Data analysis.

We used R (Version 4.4.0) (R Core Team 2024); and the R-packages fable (Version 0.3.4) (O'Hara-Wild, Hyndman, and Wang 2024a), fabletools (Version 0.4.2) (O'Hara-Wild, Hyndman, and Wang 2024b), forecast (Version 8.23.0) (Rob J. Hyndman and Khandakar 2008a), ggplot2 (Version1423.5.1;27), (Rob J. Hyndman and Khandakar 2008b), and lubridate (Version 1.9.3;29) (Grolemund and Wickham 2011), and trend (Version 1.1.6) (Pohlert 2023) for all our analyses.

A variant of the Hyndman-Khandakar algorithm (Rob J. Hyndman and Athanasopoulos 2021) was employed for the purpose of model selection. This algorithm integrates unit root tests, Akaike Information Criterion (AICc) minimization, and maximum likelihood estimation (MLE) to derive an ARIMA model.

RESULTS

A SARIMA (4, 1, 0) (0, 1, 0) $_{[365]}$ model was obtained. The model comprises an autoregressive component of order four, indicating that the value of the THI on a given day exhibits an autocorrelation of four previous days. Additionally, a differencing of one was necessary to achieve stationarity. Furthermore, a seasonal component was incorporated, where m corresponds to the 365 days of the year, also with a differencing of one.

The estimators of the model are as follows 7:

$$\begin{aligned} \tau_t &= (-0.3149\phi_{t-1} - 0.2765\phi_{t-2} - 0.3036\phi_{t-3} - 0.1904\phi_{t-4} + \varepsilon_t \\ \varepsilon_t &\sim NID(0, 2.541) \end{aligned} \tag{7}$$

The observed data (red line) and the model prediction (blue line) in Fig. 1 exhibit a similar temporal behavior for THI, indicating that the model is performing well. This conclusion can be further substantiated in the subsequent section.

In consideration of the statistical data that quantify the trajectory of the forecast, a favorable trend is discernible, indicating that the model anticipates an escalation in THI. The slope is 0.01334708, with a 95% confidence interval of [0.01026692, 0.01629877]. The Mann-Kendall trend test statistic is $S = 1.91000010^4$. The variance is 5.425116×10^6, and the $\tau = 2.875229 \times 10^{-01}$. The z-score is 8.1999, the sample size is 365, p-$<$ 0.001.

Fig. 2 illustrates that the residuals of the model exhibit a "white noise" behavior, as although some peaks are evident, they are not statistically significant. This is further corroborated by Fig. 3 showing the ACF and PACF, which indicate that the model has been estimated correctly.

DISCUSSION

This paper presents, for the first time, the behavior of the THI using an ARIMA model, for which neither AR nor MA values had been previously estimated for this animal welfare indicator. Due to their great influence on key elements for the success of livestock farming, such as production, health, and animal welfare, environmental control systems are used to maintain a series of variables, such as temperature, humidity, and contaminant concentrations, at optimal levels. These systems are the most efficient tools to guarantee better production in livestock buildings (Besteiro et al. 2017) and tools such as ARIMA models are used for this purpose. In our case, this tool was used to evaluate the use of THI data and predict its future behavior. This would contribute to the opportune use of the mechanisms that allow avoiding or reducing the effects of heat stress on farm animals, mainly dairy cattle.

The design of THI prediction models consists of two stages: estimation and forecasting. The ARIMA model selected using the Hyndman-Khandakar algorithm (Rob J. Hyndman and Khandakar 2008a) was the one with the best AICc once the PAC/ACF requirements and stationarity were met. On the other hand, the geographic sites from which the data for the construction of the THI were obtained are representative of the region. Additionally, the climate data was as complete as possible, using a total of 1,475,319 THI data to design our ARIMA model.

The initial portion of the ARIMA model indicates that the THI of the present day is autocorrelated with the four preceding days. The coefficient for the previous day (t-1) to the THI to be estimated was -0.31, while the coefficients for t-2, t-3, and t-4 were -0.28, 0.30, and 0.19, respectively. A slope was observed, necessitating differentiation to achieve stationarity. No evidence of a moving average was observed, indicating that the THI of a given day can be predicted based on the model, with a confidence

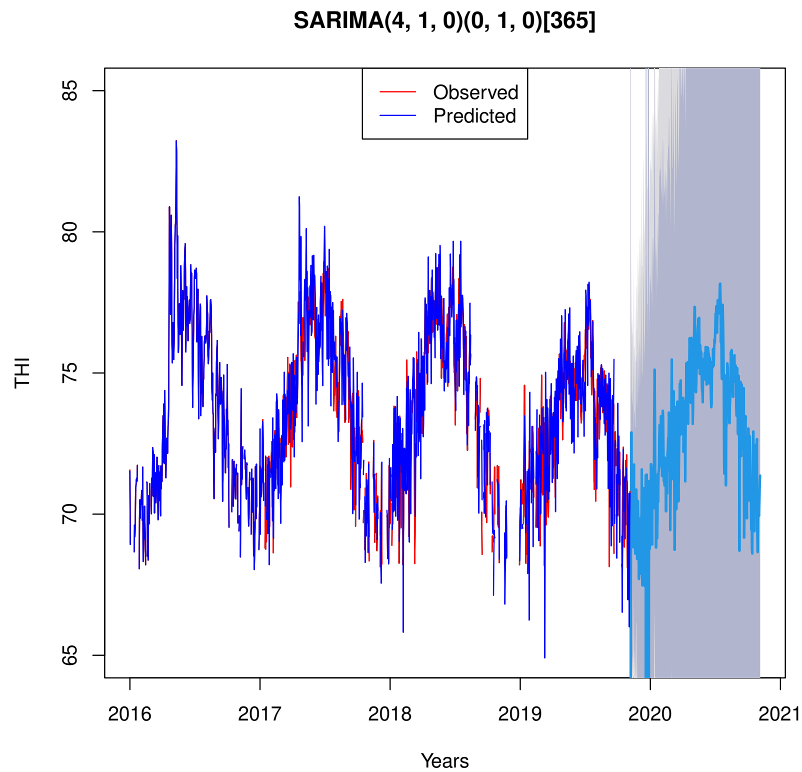

Figure 1. Time series for THI, with observed values, in red, and predicted by the model, in blue.

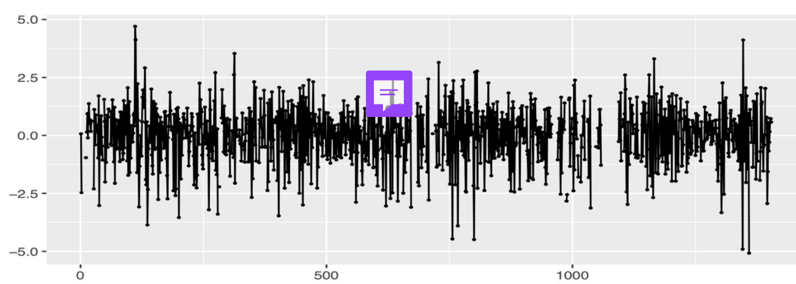

Figure 2. Residuals analysis of the model.

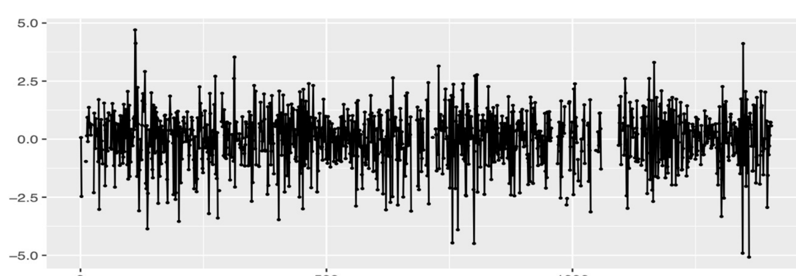

Figure 3. TAutocorrelation function (ACF), and the partial autocorrelation function (PACF) from the model.

interval of 85 %, by considering the THI values of four previous days. The second part of the model (0,1,0) allows for the detection of a seasonal pattern of 365 days, in which there is only a slope, but no autoregressive (AR) or moving average (MA) component.

With regard of the Sen's slope was 0.01334708, Mann-Kendall trend test $S = 1.91 \times 10^{04}$ (z = 8.2, n = 365, $p - value = 2.407 \times 10^{-16}$) which signifie the presence of a slope in SARIMA prediction. There is a correlation with previous reports indicating an increase in the number of days with THI levels that induce heat stress in dairy cattle. In this context, Reiczigel et al. (2009) reported an increase in the number of days per year experiencing thermal stress (THI $\geq$ 68), from 5 to 17, over the past 30 years. Similarly, (Dunn et al. 2014) proposed that by the year 2100, the number of days exceeding the thermal stress index (THI) threshold may increase from an annual average of 1-2 to over 20. Hempel et al. (2019) proposed that the impact of prospective increases in thermal stress risk will vary across locations. They posit that there will be a general trend towards an increase in the number and duration of thermal stress episodes. In their study of the Comarca Lagunera, Rodriguez-Venegas et al. (2022) observed an increase in the annual number of days with THI levels above the normal THI threshold (i.e., $\geq$ 68) over time. The observed increase in temperature has the potential to compromise the reproductive and productive soundness of Holstein cows in northern arid Mexico.

The application of ARIMA models has been demonstrated in the forecasting of pen temperatures for animals of other species. Besteiro et al. (2017) developed a model for weaned piglets that employed a complete production cycle as the model estimation stage, resulting in a model that incorporated outdoor ambient temperature as the sole independent variable. In the present study, the THI is employed as a variable, which is not a single independent variable. Rather, it entails the integration of both ambient temperature and relative humidity.

The findings suggest the possibility of further research in this region and in other locations experiencing elevated temperatures. The objective is to develop mathematical models that can accurately predict the THI with a high degree of probability. Such knowledge would facilitate the implementation of strategies to mitigate the adverse effects on livestock health and productivity.

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