Journal of Agriculture and Environment for International Development - JAEID 2025, 119 (2): 185-198
DOI: 10.36253/jaeid-18519

Spatial variation of climate change-induced heat stress risk for dairy cows in Botswana

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Abstract: The southern African region is considered a “climate change hotspot” due to its projected substantially warmer and drier future. Therefore, there is a need to determine the likely impact of climate change-induced heat stress on dairy farming across ecological regions in the country. This study’s goal was to determine the recent and future spatially differentiated dispersion of heat stress conditions for dairy cattle across Botswana for the recent (2020), near-term (2030), mid-term (2050), and long-term (2070) under the high greenhouse gas emission scenario using the temperature humidity index. Results show an increase in the temperature humidity index ranging from 73.35 to 79.18 in 2020; 76.01 to 81.30 in 2030; 77.76 to 84.16 in 2050; and 79.60 to 85.84 in 2070. Areas in the north, i.e., Northwest, Northeast, and northern parts of the Central and Ghanzi Districts, are projected to record higher maximum temperatures, higher temperature humidity index, a greater number of heat stress days, and experience a higher degree of heat stress severity than those in the south of the country, i.e., Southern, Kgatleng, Kweneng, and Kgalagadi districts. Thus, the intensity of heat stress is projected to increase as you go further north in the country. The spatial variability of heat stress intensity implies that without the implementation of adaptation measures, the entire country could experience dairy farming challenges due to heat stress in the future, exacerbating the already dire dairy production environment in the country. Future policies and programs for developing the dairy sector in Botswana should thus factor in the heat stress challenge to attain the intended objectives.

KEYWORDS: Climate Projections, SSP 5-8.5, Temperature humidity index, Spatial Variation, Adaptation strategies

Introduction

Climate change is a global phenomenon, but its impacts are felt at varying degrees in different parts of the world (Byakatonda et al., 2018; Rahimi et al., 2020). At a global scale, reports point to a continued rise in ambient temperatures by 1.1 °C in 2019 compared to the pre-industrial period (1850-1900) (IPCC, 2021; Mupangwa et al., 2023). As the global temperatures increase, it has been shown that the climate and weather variability will also increase (Umar et al., 2019; Nyoni et al., 2021). The southern African region is considered a “climate change hotspot” due to its projected substantially warmer and drier future (Engelbrecht et al., 2024). An earlier study by Nkemelang et al. (2018) revealed that Botswana is warming faster than the global average, with a more noticeable increase in mean and maximum temperatures. Several studies have shown that climate change is likely to increase the risk of variations in temperature and rainfall (Byakatonda et al., 2018; Nkemelang et al., 2018; Umar et al., 2019), leading to increased occurrence of droughts and extreme daily temperatures, though not in a spatially uniform manner (Lyon, 2009; Nkemelang et al., 2018).

Rising temperatures and frequent and intense heat waves that are associated with climate change (Moses, 2017; Mbokodo et al., 2020) pose a significant challenge to the livestock industry (Carvajal et al., 2021). These high temperatures cause increased heat loads in animals and compromise their ability to dissipate excess heat to maintain a thermal equilibrium, resulting in heat stress (Collier et al., 2019). Dairy cows are more susceptible to heat stress challenge given their high metabolic heat loads (Angel et al., 2018), which negatively affects their health, productivity, and welfare (Summer et al., 2018; Woodward et al., 2025). The impact of elevated temperatures causes dairy farmers to incur economic losses due to declines in milk yield, poor reproduction, and increased incidences of diseases (Kadzere et al., 2002; Renaudeau et al., 2012; Das et al., 2016). Moreover, heat stress compromises animal welfare as it leads decline in feed intake and rumination (Messeri et al., 2023), reduction of time spent lying down (increased standing) (Frigeri et al., 2023), increased respiration rates (panting) (Osei-Amponsah et al., 2020), and may lead to cow mortalities in extreme cases (Bishop Williams).

To study heat stress in dairy cattle, several thermal indices have been developed in the past decades, with the most popular being the temperature-humidity index (THI) (Dikmen & Hansen, 2009; Jeelani et al., 2019). This index (THI) utilizes ambient temperature and relative humidity in its calculation (Key et al., 2014). Thus, the THI tends to increase when the temperature and/or the relative humidity increase (VanderZaag et al., 2023). Several studies have reported a negative relationship between THI and dairy cow production parameters such as milk yield (Niyonzima et al., 2022; Chen et al., 2024), reproduction (Boni et al., 2013; Djelailia et al., 2020), and milk composition traits (Hammami et al., 2013; Bertocchi et al., 2014).

In Botswana, dairy farming is still in its infancy and is mostly practiced by small-scale farmers who keep fewer than 50 milking cows per farm (Mariri, 2021). This sector has not seen any significant growth in the past decades, owing to various challenges such as high input costs (mostly feed), low productivity (low yields and poor reproduction), and poor access to markets (Baliyan & Gosalamang, 2016a). The growth of this sector is most likely to be further hampered by climate change, given that the country has an arid to semi-arid climate. Climate change projections show that Botswana is likely to become hotter and drier in the coming decades (Nkemelang et al., 2018; Akinyemi & Abiodun, 2019). Therefore, there is a need to determine the potential heat stress challenge for dairy cattle. Due to the high spatial variability of meteorological parameters such as air temperature (Mupangwa et al., 2023), relative humidity (Nyoni et al., 2021), and rainfall (Umar et al., 2019; Mengistu et al., 2020), in semi-arid climates such as Botswana, it is imperative to determine the likely impact of climate change on dairy production spatially explicitly for the development of spatially disaggregated policy recommendations. Therefore, this study's goal was to determine the recent and future spatially differentiated dispersion of heat stress conditions for dairy cattle across Botswana for the recent (2020), near-term (2030), mid-term (2050), and long-term (2070) under the high greenhouse gas emission scenario using the temperature humidity index.

Materials and Methods

Study area

This study was conducted in the landlocked country of Botswana, which is located centrally in the southern region of Africa (Figure 1). The country is situated between 18º and 27º south latitude, and 20º and 30º east longitude. Altitude for Botswana ranges from 660 meters to 1,490 meters, with the mean altitude of 1000 meters above sea level. The country has a surface area of 58,1730 Km^2 with about 84% of the land covered by the Kalahari Desert. The climate of Botswana is mainly arid in the central and western areas (which are mostly covered by the Kalahari Desert), and semi-arid in the southern and eastern areas (Moalafhi et al., 2013).

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Botswana's climate is characterized by highly erratic rainfall and warm to hot temperatures (Akinyemi & Abiodun, 2019) i.e., mean monthly maximum temperature ranges between 29.5 °C and 35 °C in the summer, and low precipitation rates, ranging from 250 mm in the southwest to 650 mm in the northeast (Mphale et al., 2018; Matopote & Joshi, 2024).This study used 24 synoptic weather stations spread across 9 administrative districts in Botswana.

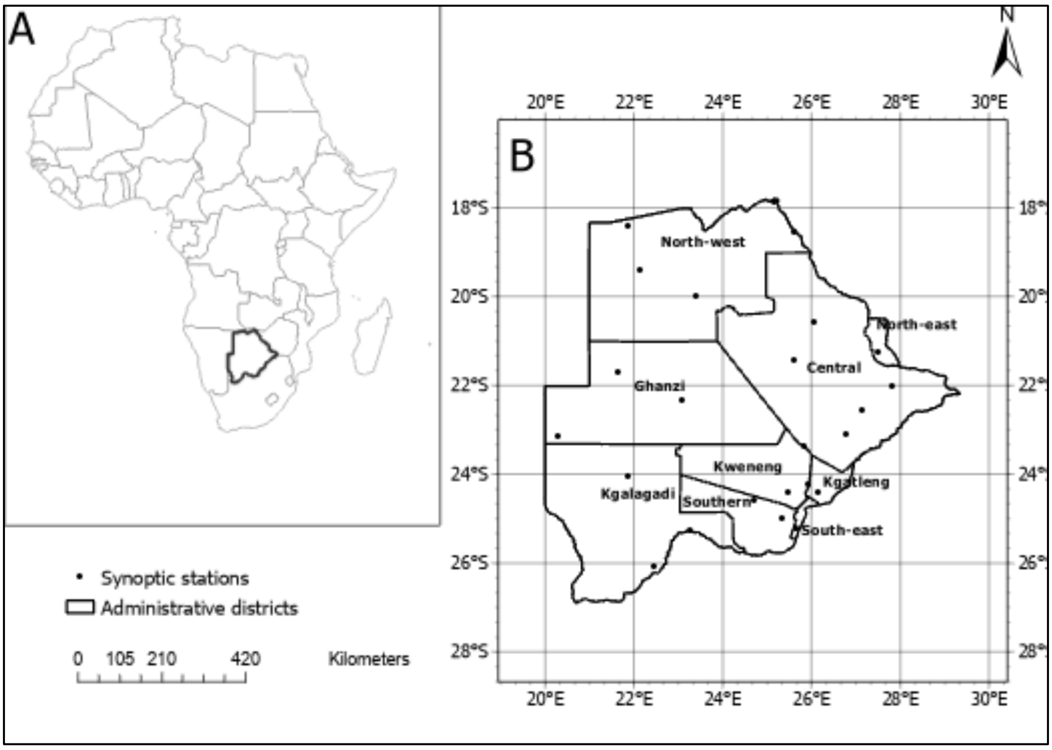

Figure 1. Location of Botswana in Africa (A), the administrative districts, and the spatial distribution of the synoptic weather stations used in this study (B)

Dairy farming in Botswana

Dairy farming remains one of the least performing livestock sectors in Botswana and lags far behind beef production (Moreki & Tsopito, 2013). This situation has led to the country being a net importer of milk and dairy products, mostly from neighbouring South Africa (Mariri, 2021). Botswana’s dairy cow population was estimated at around 2,900 cows, with about 1,350 milking cows (Ministry of Lands and Agriculture, 2023). Generally, most dairy farms in Botswana are small-scale producers with less than 50 milking cows (Mariri, 2021). Botswana’s national dairy herd is mainly made up of exotic dairy breeds i.e., Holstein Friesians, Jersey, Brown Swis and crosses of these breeds. The Holstein Friesian breed, which is renowned for its high milk yielding capacity is the most popular breed kept by dairy farmers in Botswana and constitutes over 50% of Botswana’s dairy herd (Mariri, 2021). Generally, dairy cows in Botswana are low yielding with the national daily milk yield averaging around 12 kg/cow/day (Ministry of Lands and Agriculture, 2023). This low milk output is attributable to high feed costs that leads to insufficient feeding, feed shortage and unavailability locally, and lack of technical support (Baliyan & Gosalamang, 2016). Due to Botswana’s hot and dry climate which limits pasture availability, majority of dairy farmers practice intensive farming system (zero grazing), where cows are fed totally mixed rations and housed on open sheds roofed with corrugated irons sheets to protect the cows from weather elements (rain and direct sunlight).

Climate Projections and current weather data

Climate projections from phase six of the Coupled Model Intercomparison Project (CMIP6) were utilized in this study. The high greenhouse gas emission scenario, namely the shared socioeconomic pathway - SSP5-8.5, was used. This scenario assumes a radiative forcing of 8.5 W $^{m-2}$ by 2100 (Meinshausen et al., 2020). It was chosen as previous studies have shown that Botswana is warming at a higher rate than the global average (Nkemelang et al., 2018; Akinyemi & Abiodun, 2019). The future storylines/pathways are described in detail in Riahi et al. (2017). The climate projections downloaded were for the short-term (2030), mid-term (2050), and long-term (2070). The climate parameters of interest were maximum temperature and relative humidity. Three Global Climate Models (GCMs) were used being: ACCESS-CM2, GFDL-ESM4, and the MPI-ESMI-2-LR. The climate projections were downloaded for each of the 24 weather stations used in this study. The weather data for the year 2020 (daily maximum temperature and relative humidity) were downloaded from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) website using the coordinates for the 24 weather stations.

Temperature Humidity Index

The temperature humidity index (THI) is a unitless single value that represents the combined effects of temperature and relative humidity. This index is a better indicator of heat stress than using temperature alone (Key et al., 2014). In this study, THI was calculated using the National Research Council (1971) equation depicted below(1). An average of the three GCMs was used to represent the daily maximum THI for each weather station.

$$THI = (1.8 \times T_{max} + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T_{max} - 26) \quad (1)$$

where T_{max} is the maximum daily temperature (°C), and RH is the relative humidity (%).

Severity of heat stress

The daily maximum THI was used to calculate the number of heat stress days for 2030, 2050, and 2070, for each weather station. These were classified as mild heat stress ($72 \geq THI < 79$), moderate heat stress ($79 \geq THI < 89$), and severe heat stress ($THI \geq 89$) (Balcha et al., 2024).

Mapping of the heat stress conditions

The daily weather data for 2020 and the climate projections for 2030, 2050, and 2070 were captured in Microsoft Excel for each of the 24 weather stations, including their latitude and longitude coordinates. Mapping was performed using the ordinary kriging technique in the ArcGIS Pro 3.0.5 software, as depicted in the flowchart presented in Figure 2. The analysis was carried out for the maximum temperature, temperature humidity index, and heat stress days (the number of days with THI above the heat stress threshold for dairy cows of 72), and the severity of heat stress. The kriging tool is an advanced geostatistical procedure that enables estimating a surface from scattered points with z-values using a semi-variogram (Oskouei et al., 2022). Thus, kriging enables prediction for an unmeasured location using weights of the measured surrounding values (Mhlanga et al., 2018). It also enables the generation of maps, and it is usually preferred as it produces unbiased estimates with minimum variance (Oliver & Webster, 2014).

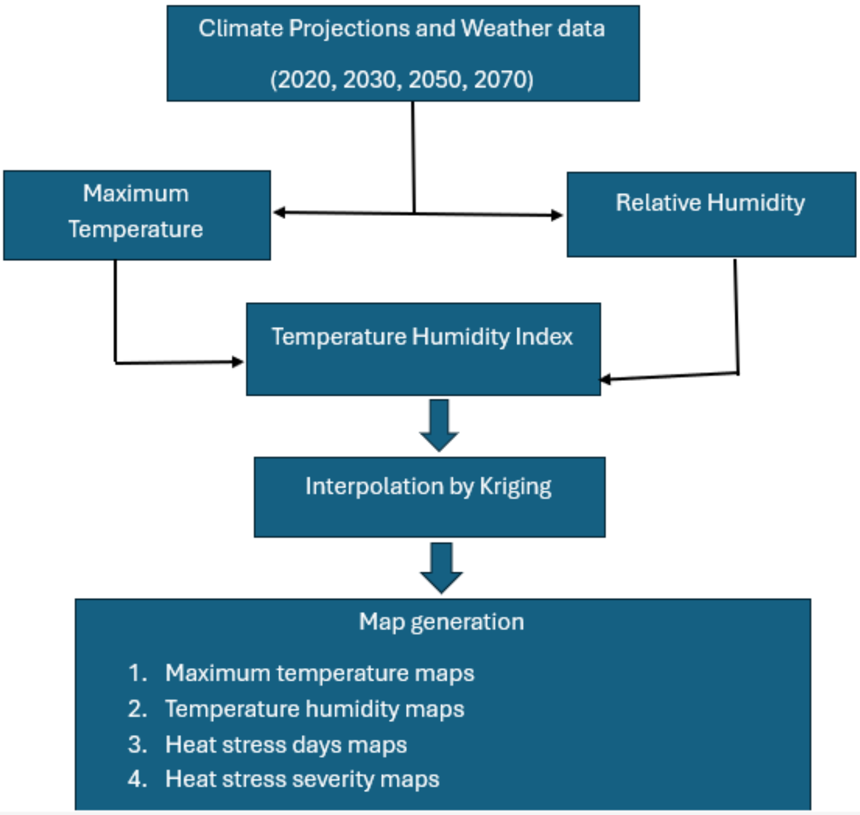

Figure 2. Flowchart for the geoprocessing of data during the mapping exercise

Results

Spatial variation of maximum air temperature

The results for the spatial analysis of the variation in the mean maximum temperature for the present (2020), near-term (2030), mid-term (2050), and long-term are shown in Figure 3. The results depict an increase in annual mean maximum temperature both in time and space. In 2020, the annual mean maximum temperature ranged from 28 °C in the Southern District to 31.8 °C in the Northwest District. In 2030, the annual mean maximum temperature ranged from 29 °C in the Southern District to 33.1 °C in the Northwest District. For 2050, the annual mean maximum temperature ranged from 30.6 °C in the Southern District to 34.9 °C in the Northwest District, while in 2070 it ranged from 31.9 °C in the Southern District to 35.8 °C in the Northwest District. Very hot conditions are projected for 2070, with the whole country recording annual mean maximum temperatures above 32 °C. Projections show that the Northwest, Ghanzi, northern parts of the Central District, and the northern parts of Kgalagadi District will record annual mean maximum temperatures above 34 °C in 2070.

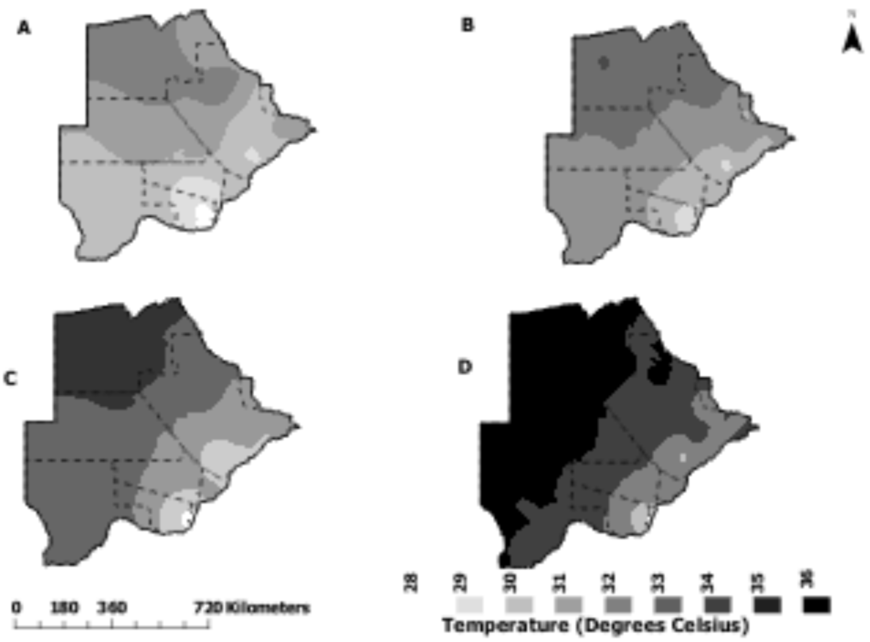

Figure 3. Spatial variation of maximum temperature for Botswana for 2020 (A), 2030 (B), 2050 (C), and 2070 (D)

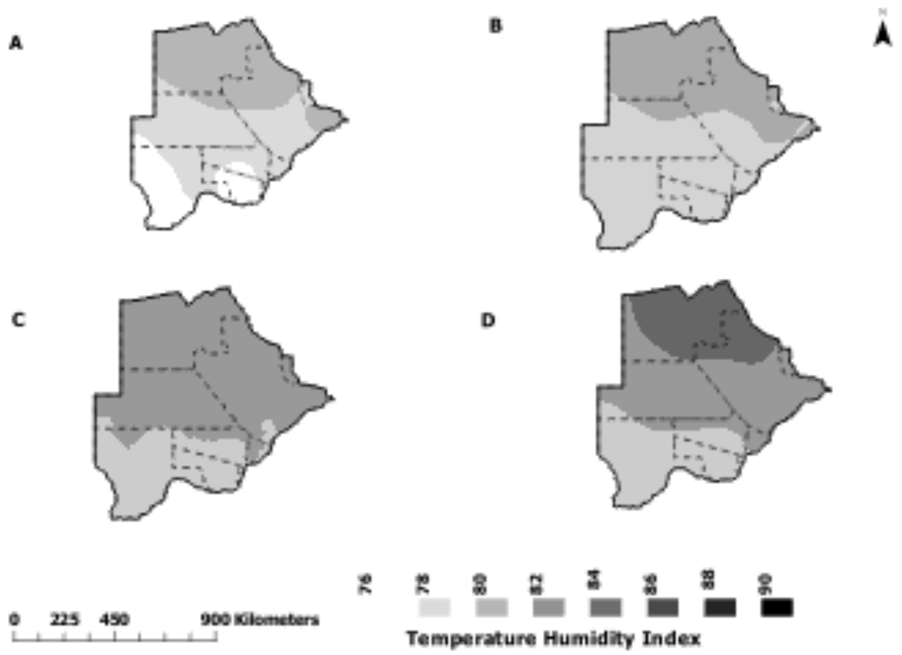

Figure 4. Spatial variation of temperature humidity index for Botswana for 2020 (A), 2030 (B), 2050 (C), and 2070 (D)

Spatial variation of Maximum Temperature Humidity Index

The results for the spatial variation in annual mean THI for 2020,2030,2050, and 2070 are presented in Figure 4. In 2020, THI ranged from 75.4 in the Southern District to 79.2 in the Central District, while in 2030 it ranged from 76.0 in the Southern District to 81.3 in the Central District. For 2050, THI ranged from 77.8 in the Southern District to 84.2 in the Northwest District, whereas in 2070, THI ranged from 79.6 in the Southern District to 85.8 in the Northwest District. An increasing trend in THI is evident from the present term to the long term. The spatial

DOI: 10.36253/jaeid-18519

analysis also reveals an increase in THI from south to north, i.e., higher THI for areas in the north than in the southern parts of the country.

Spatial variation of heat stress days

This study adopted THI > 72 as the threshold for the onset of heat stress in dairy cattle. The main results for spatial variation in the number of days of exposure to heat stress conditions for dairy cattle are shown in Figure 5. In 2020, the number of heat stress days ranged from 247 in the Kgalagadi District to 335 in the Northwest District, while in 2030 they ranged from 270 in the Southern District to 365 in the Northwest District. For 2050, heat stress days ranged from 289 in the Southern District to 365 in the Northwest District, while in 2070 they ranged from 322 in the Southern District to 365 in the Northwest District. The spatial analysis depicts an increasing trend in the number of heat stress days from south to north. In 2050, projections show that the whole of the Northwest District, Northeast District, northern parts of the Central and Ghanzi Districts will all record above 340 days of heat stress. In the long term (2070), the whole country of Botswana is projected to have over 320 heat stress days per year, while the Ghanzi District, Northwest District, and areas in the northern parts of the central district are projected to record 365 days of heat stress.

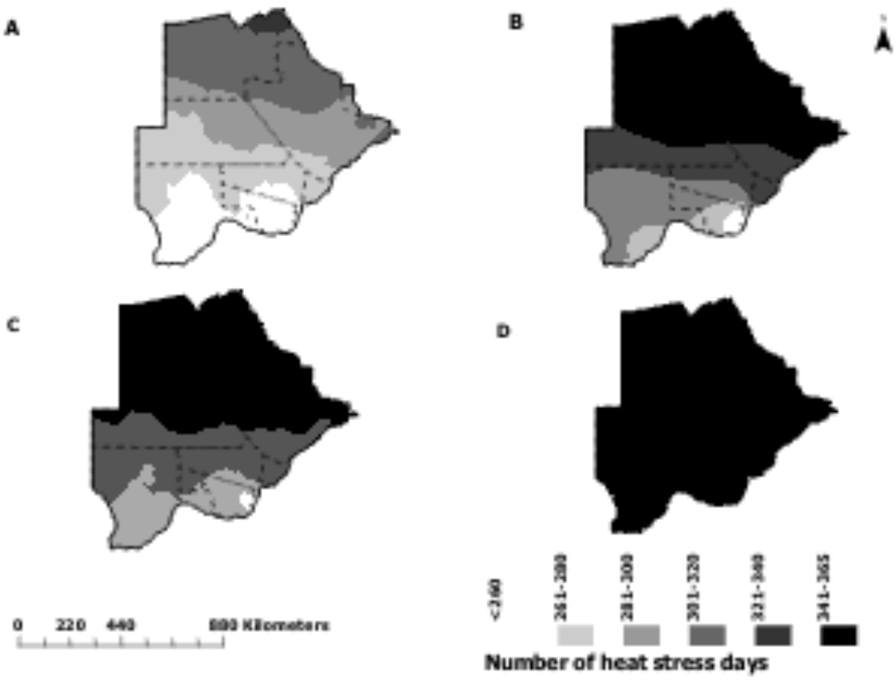

Figure 5. Spatial variation of heat stress days for Botswana for 2020 (A), 2030 (B), 2050 (C), and 2070 (D) based on maximum THI

Severity of heat stress for the future period

The main results for the future severity of heat stress for the near-term (2030), mid-term (2050), and long-term (2070) are shown in Figure 6. The frequency of the number of days with mild heat stress range from 29.6% (108 days) in the Northwest District to 45.8% (167 days) in the Central District; moderate heat stress ranged from 33.4% (122 days) in the Southern District to 69.6 % (254 days) in the Northwest District, while the frequency of severe heat stress was below 5% in 2030. The Central District and northern areas are projected to be dominated by moderate heat stress, while the mild heat stress dominated the eastern areas (Kweneng, Kgatleng, Southeast, and the southern parts of the Central District). In 2050, projections show the frequency of mild heat stress ranging from 17.3% (63 days) in the Northwest District to 35.3% (129 days) in the Central District; moderate heat stress ranged from 47.7% (174 days) in the Southern District to 68.2% (249 days) in the Northwest District, while severe heat stress ranged from 0 – 17.3% (0 – 63 days). Severe heat stress was projected to be localized around the Kasane and Pandamatenga area in the Northwest District. For 2070, the frequency of mild heat stress is projected to range from 13.2% (48 days) in the Northwest District to 34.8% (127 days) in the Southern District, moderate stress ranged from 45.8% (167 days) in the Central District to 66.3% (242 days) in the Ghanzi District, while severe heat stress ranged from 0 – 31.2% (0 -114 days). In all three projection periods, moderate heat stress was shown to be the most dominant category of heat stress. However, an increase in the number of severe heat stress days is also projected, particularly in the northern parts of Botswana.

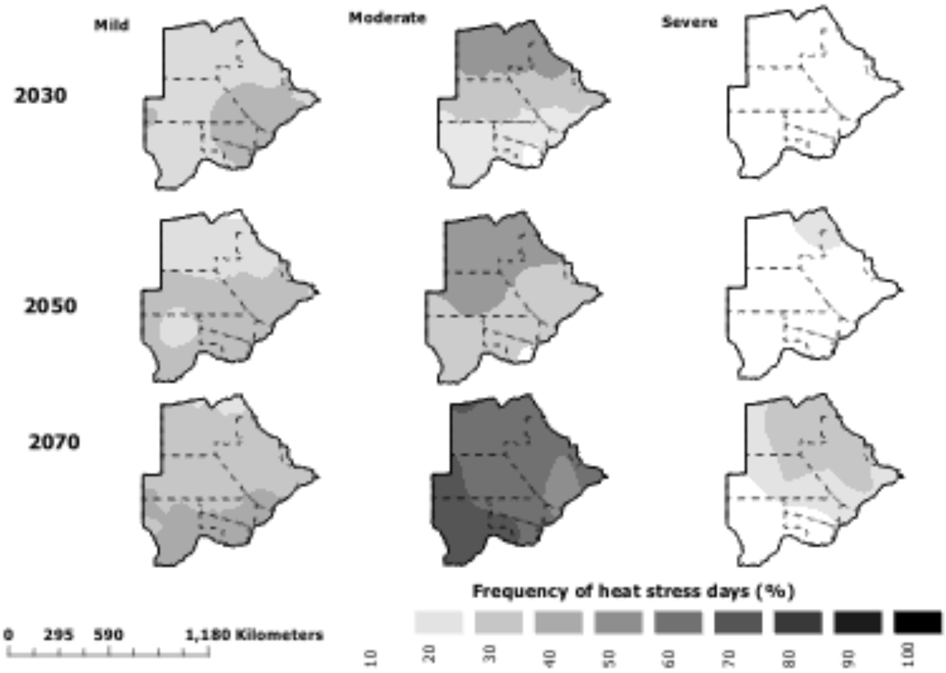

Figure 6. Projected severity of heat stress for 2030 (top), 2050 (middle), and 2070 (bottom). N.B.: mild heat stress (72≥THI<79), moderate heat stress (79≥THI<89), and severe heat stress (THI≥89)

Discussion

Heat stress is a major constraint to livestock production, particularly in tropical and arid areas (Rahimi et al., 2021). This heat stress challenge will be further exacerbated by climate change, with greater risk in semi-arid climates (Mauger et al., 2015) such as that of Botswana. This study was undertaken to determine the spatial variability of the risk of heat stress in Botswana in the present term (2020), and three future periods (2030, 2050, and 2070) using the THI. Meteorological data for the present term show that maximum temperatures in Botswana are already high, predisposing cattle to heat stress. Results from the climate projections depict a warming phenomenon with an increase in temperature being projected. Our mapping of the THI shows that dairy cows are already exposed to very high THI, and this will progressively increase in future periods. Dairy cattle suffer from heat stress when THI exceeds the critical comfort level of 72 (Balcha et al., 2024). Dairy cattle exposed to THI above 72 have been shown to have a decline in feed intake (Chen et al., 2024), reduced rumination (Messeri et al., 2023), increased frequency and quantity of water consumption (Correa-Calderón et al., 2022), high respiration, sweating, and heart rate (Yan et al., 2021), which ultimately results in a decline in milk yield

(Gorniak et al., 2014; Niyonzima et al., 2022; Habimana et al., 2023). High THI is therefore very detrimental to dairy cow productivity and hampers the viability and profitability of dairy farms. Our analysis revealed that the number of heat stress days for dairy cows is already exorbitant and is projected to increase, with some areas experiencing heat stress for 365/365 days in 2030, 2050, and 2070.

Findings from this study show an increase in the severity of heat stress from 2030 to 2070. Moderate heat stress (72>THI<79) dominated for all three future periods. An increase in the severity of heat stress was also reported in the Tigray region of Ethiopia (Balcha et al., 2024) and in West Africa (Rahimi et al., 2020). In another study, Rahimi et al 2021 reported an increase in the frequency of severe/Danger (THI>89) in East Africa. The projected increase in the severity of heat stress consequently leads to a decline in the area suitable for dairy production unless adaptation and mitigation measures are implemented. Our results show that the whole of Botswana is not suitable for dairy farming, and the situation will worsen in the future. Reduction in the area suitable for dairying is a worrying trend and has been reported by authors in southern Africa, e.g., South Africa (Nesamvuni et al., 2012; Williams et al., 2016), and Zimbabwe (Mhlanga et al., 2018).

Our spatial analysis shows that areas in the north are projected to record higher maximum temperatures, higher THI values, a greater number of heat stress days, and experience a higher degree of heat stress severity than those in the south of the country. Thus, the intensity of heat stress increases as you go further north in the country. This trend is to be expected, as earlier works have projected Botswana to be the hardest hit country by climate change in the southern African region. The interior regions of southern Africa are likely to warm at a higher rate than tropical Africa (Engelbrecht et al., 2024). Our findings corroborate those from Mphale et al. (2018), who reported that areas in the north of Botswana (Kasane, Maun, Shakawe) were warmer than those in the south of the country (Ghanzi, Mahalapye, Tsabong, Tshane). In the same vein, a spatial analysis by Byakatonda et al., (2018) reported an increased warming for areas in the north, east, and west of the country. This warming trend could be attributable to the effect of the Kalahari Desert, as areas in its proximity show a higher degree of warming. Moreover, due to the low vegetation cover and soil aridation, there is a reduction in surface emissivity, which consequently results in warming and increases in maximum temperatures (Zhou et al., 2007).

Under the high greenhouse gas emission scenario, projections reveal that mean monthly temperatures are expected to increase by 2.5 °C in 2050 and by 5 °C by the end of the century for Botswana (The World Bank Group, 2021). Moalafhi et al., (2013) projected a steeper increase in temperature for Botswana of 3.7 °C by 2050. In addition, heat waves are also projected to increase in all regions of the country (Moses, 2017; Nkemelang et al., 2018), with an increase in the number of hot days and nights (The World Bank Group, 2021). This high warming phenomenon in the central interior of southern Africa is mainly due to a "strengthening of mid-level anticyclonic circulation and subsidence, which suppresses cloud formation and rainfall, resulting in more solar radiation reaching the surface, thereby driving the relatively high rate of temperature increase." (Engelbrecht et al., 2024). Moreover, Botswana has a semi-arid hot steppe (Koppen's BSh) climate, thus making it vulnerable to climate extremes (Akinyemi & Abiodun, 2019).

Given the magnitude of the increase in the severity of heat stress for dairy cows revealed by this study, it is imperative that dairy farmers implement adaptation measures in their farms to abate the effects of heat stress on their cows. Approaches that seek to modify the environment to make it conducive despite the high ambient temperatures would go a long way in helping dairy cows stay productive. Such approaches include planting trees to provide shade, and provision of roofed cow barns using materials such as grass thatch or corrugated iron sheets (Ekine-Dzivenu et al., 2020) which are helpful in protecting the cows from direct solar radiation

(Gunn et al., 2019). Additionally, farmers can improve ventilation inside the cow barns with cooling fans (Vroege et al., 2023). Where feasible the use of water sprinklers, air-conditioning or high-pressure evaporative cooling may be practiced (Gunn et al., 2019). Dietary interventions such as lowering the fiber content and increasing fat content of the feed have also been shown to be a viable approach to minimize the impacts of heat stress (Yadav et al., 2023). Supplementation with minerals zinc, vitamins A, C, and E have been shown to lower the oxidative stress caused by heat stress (Sejian et al., 2018). Genetic selection for heat tolerance is another alternative that may offer a lasting solution. The current practice of keeping exotic dairy breeds in the hot semi-arid climate of Botswana is unsustainable. To improve heat tolerance, crossbreeding exotic breeds with native breeds (Bos Indicus) which are adapted to hot tropical climates is a viable option (Yadav et al., 2023). Future research should explore cost-effective heat abatement strategies that can work effectively under hot semi-arid conditions such as that of Botswana.

Conclusion

This study mapped the risk of heat stress for dairy cattle in Botswana in the present (2020), near-term (2030), mid-term (2050), and long-term (2070) using the temperature-humidity index as an indicator of heat stress. The study revealed a warming trend from the present term, which intensifies in the long-term. An increase in the number of days that dairy cattle will be exposed to heat stress was also observed. In addition, an increase in the severity of heat stress was also noted. The increase in maximum temperatures, THI, number of heat stress days, and the severity of heat stress has negative implications for the dairy sector in Botswana, which is still in its infancy. Therefore, the need for further research on cost-effective heat abatement measures that dairy farmers can adopt cannot be overemphasized. Additionally, future research should determine both daytime and night-time THI thresholds for dairy cows in Botswana and quantify the number of hours cows spend above these thresholds. This will help farmers make informed decisions regarding managing their cows to minimize impacts of heat stress. The mapping exercise undertaken in this study shows that the whole country will not be suitable for dairying without the implementation of adaptation measures due to heat stress. Future policies and programs for developing the dairy sector in Botswana should thus factor in the heat stress challenge to attain the intended objectives.

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