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Original Research Paper

Integrating Pasture Vegetation Diversity to Improve Environmental Comfort and Welfare in Grazing Livestock Systems

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Key Words

Heat stress reduction,
Grazing behavior,
Soil moisture balance,
Nature-based solutions,
Sustainable grazing systems,
Cattle and small ruminants.

Abstract

The pasture vegetation is important in stabilising the microclimatic conditions in grazing landscapes hence having a direct impact to the livestock comfort, behaviour and the general livestock welfare. This paper examines how the different degrees of pasture plant diversity affect thermal balance, soil water movement, as well as the grazing enthusiastic behaviour of cattle and small ruminants. In depth environmental values such as canopy shade, surface temperature, air humidity and soil moisture measurements are taken, as well as physiological measurement values that were made including respiration rate, body temperature, and grazing duration. The results demonstrate that high-diversity pastures were constant in creating cooler and stable micro classifications, amplifying the capacity of the land to keep water moisture, and also enabling better work to be done by the rulers. Symptoms of heat stress in livestock in such habitats were significantly less than in low-diversity pastures. The study highlights the importance of biodiversity-enhanced pastures as a viable nature-based intervention to enhance the livestock thermal comfort and sustainable management of grazing systems by showing that there is a strong correlation between terrestrial diversity and livestock thermal comfort.

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Introduction

The pasture vegetation has been seen to be a key player in the control of the microclimatic conditions in the grazing systems where change in plant diversity is directly proportional to moderation of temperatures, soil moisture contents as well as the stability of the environment. The variety in vegetation structures enhance the ecological performances by increasing the levels of shading, evapotranspiration and soil-water engagements, resulting in the provision of more favourable microhabitats to grazing livestock. Such systems of nature are acknowledged as critical elements in the sustainable agricultural landscapes, especially with the producer trying to find ways to enhance the natural capital and ecosystem sustainability (Ascui & Cojoianu, 2019; Cohen-Shacham et al., 2016; Teague & Kreuter, 2020). Figure 1 demonstrates the ecological pathways in which vegetation communities manipulate the thermal environments by interacting conceptually with vegetation diversity, microclimate and livestock comfort. Animals, particularly cattle and small ruminants are very vulnerable to thermal stress, and changes in heat load on environmental conditions may have drastic influences on the behaviour, grazing activities, and the welfare state. Extreme weather conditions of high temperatures and low moisture intensify the physiological stress reactions, such as high respiration rate and high body temperature that further diminishes the amount of feed intake, productivity, and wellbeing. The adaptive grazing management has been discussed (Bilotto et al., 2023; O’Reagain et al., 2014; Pulido et al., 2018) as a vital crop in the past by the research that addresses the climatic variability reduction and the functioning of the ecosystem in the rangelands. Nevertheless, most research has mainly centred on grazing severity and land status yet little has been realised on the actual contribution of vegetation diversity as a thermal buffer involved in livestock productions.

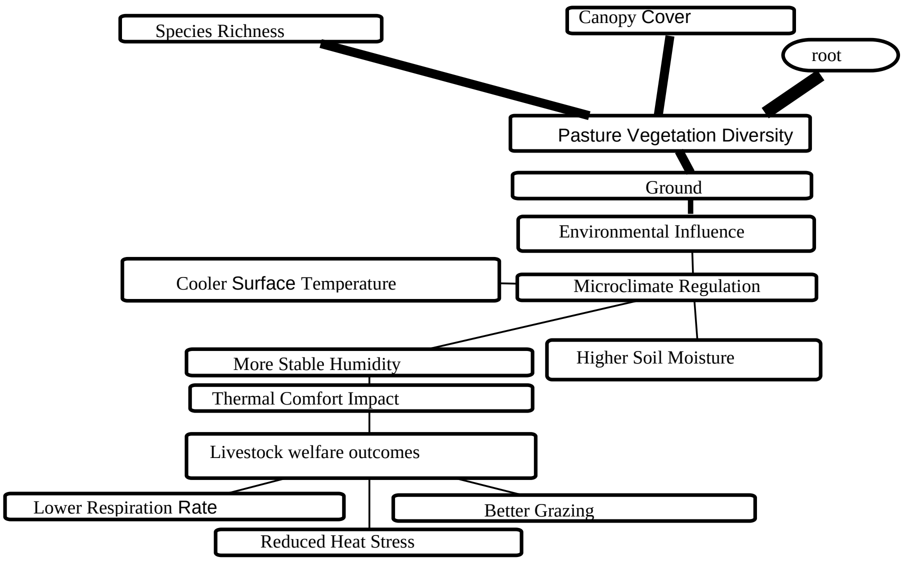

Figure 1: Conceptual Framework Showing the Influence of Pasture Vegetation Diversity on Microclimate and Livestock Welfare

Over the recent years, nature-based solutions have become a solid concept to respond to the climate-related issues in agro ecosystems, which promotes the consideration of intervention aimed at benefits relying on betterment of biodiversity to support ecological and economic performance simultaneously (Cohen-Shacham et al., 2016; Fleming et al., 2022; Issb, 2023). Planting a variety of plant species in pastures has been reported to enhance the health of the soil, strengthen the stability of the forage, and promote sustainability of grazing ventures in the long run (Bowen & Chudleigh, 2018; van Putten et al., 2021; Whitten et al., 2019). However, even with these improvements, quantitative modelling does not provide a connexion between vegetation diversity, microclimate dynamics, and livestock comfort physiological indicators. This limitation prevents land managers and policy makers to formulate evidence-based plans on how to have climate-resilient livestock systems.

To fill this gap in knowledge, the current study will consider the impacts of different amounts of diverse pasture plants in regulating thermal conditions, moisture content of soil, and welfare behaviours in grazing livestock. The study, through the integration of field-based measurements of the environment with the aid of the Light Gradient Boosting machine (LightGBM) framework, is able to determine the most significant environmental factors that influence livestock thermal comfort. LightGBM is especially well-adapted to this analysis since it can be used when dealing with nonlinear ecological interactions and a high-dimensional environment dataset. The results will be to offer factual background to support vegetation diversity as a nature-based method of enhancing the wellness of livestock, enhancing ecosystem service, and sustaining pasture-based management in the rising climate uncertainty.

Literature Review

The diversity of pasture vegetation contributes to the establishment of the ecological processes and the environmental conditions in grazing landscapes in an essential way. Previous research studies have been able to show that the presence of various plant communities enhances soil moisture levels, ground cover stability and helps lower surface temperature due to heightened shading and evapotranspiration action (Bowen & Chudleigh, 2018; Pulido et al., 2018; Stone et al., 2021; Teague & Kreuter, 2020). Change in vegetation structure may have very strong impact on the balance of energy and wind circulation resulting in microclimatic gradients that directly impact livestock thermal exposure. As a brief overview as summarised in Table 1, studies of the various rangeland systems indicate that even to a heterogeneous group of plants the environmental extremes can be buffered and more resiliency in grazing systems can be facilitated.

Regulation of microclimate is one of the most important consequences of vegetation diversity, and a number of studies have indicated the importance of shade, canopy height and vegetative density in the control of the amount of heat on the grazers. Lower surface temperatures and better moisture dynamics in the soil provide cooler micro habitats, which subsequently minimises the body temperature, respiration rate and feeding behaviour by causing physiological stress reactions (O’Reagain et al., 2014; Pulido et al., 2018; Sathya & Geetha, 2017). Despite rising climatic variability, heat stress is a significant limitation to grazing livestock production, and vegetation-mediated temperature regulation is an important ecological service to the wellbeing of animals.

In addition to thermal control, other pasture regimes have also been linked to better livestock behaviour patterns as well as livestock welfare. Increased vegetation complexity leads to more favourable grazing through the support of habitual forage intake and the choice of feeding including the diminished duration that the animal gravers search appropriate forage. It has also been found that cattle in heterogeneous pastures have greater movement efficiency and a decrease in stress behaviours as well as have better health results, as multifaceted advantages of ecological heterogeneity in pastoral agribusinesses (Bowen & Chudleigh, 2018; O’Reagain et al., 2014; Teague & Kreuter, 2020). These results add to the realisation that not only microclimate is a biophysical driver in vegetation structure, but also a determinant of animal performance and welfare.

Recent innovations in machine learning have provided novel possibilities of studying complicated interactions in grazing ecosystems. Ensemble learning models based on trees, such as Random Forest, XGBoost and LightGBM are on the spotlight because of their capacity to represent nonlinear interactions of biological response and the environmental factors. LightGBM, specifically, has proven to be very popular in the agricultural and ecological research due to its comparative computational efficiency, scalability, and readability with multi-dimensional datasets (Janaki Sathya & Geetha, 2011; Kumar et al., 2018; Rusdiana & Suhendi, 2025; Ishrat, 2024). Nevertheless, the application of LightGBM to simulate the joint effects of vegetation diversity and patterns of microclimate on livestock thermal comfort has not been well studied in current scholarly literature, even though increased attention is paid to the use of ML-based predictive frameworks. This gap has been filled through this study, which incorporated empirical field measurements and LightGBM to determine the most influential environmental factors that affect the livestock welfare in various grazing areas.

Table 1: Summary of Key Studies on Vegetation Diversity, Microclimate Regulation, and Livestock Heat Stress

Study / Reference	Vegetation Diversity / Pasture Condition	Microclimate Regulation Effects	Livestock Heat-Stress Outcomes	Key Findings
Bowen & Chudleigh, 2018	Buffel grass pastures with varied grazing pressure	Improved soil moisture retention under moderate vegetation cover	Reduced thermal exposure in moderately grazed paddocks	Balanced grazing improves land condition and lowers heat risk
O'Reagain et al., 2014	Diverse rangeland vegetation in northern Australia	Stabilized microclimates through better canopy structure	Lower heat-stress indicators due to moderated temperatures	Sustainable grazing enhances ecosystem resilience
Pulido et al., 2018	High vs. low pasture cover in semi-arid rangelands	Reduced surface temperature under high-cover sites	Lower body temperature and respiration rate in livestock	Heavy grazing degrades microclimate and increases heat stress
Teague & Kreuter, 2020	Multi-species regenerative grazing systems	Enhanced shading, cooler soil surfaces, higher humidity	Significant reduction in animal stress behavior	Regenerative grazing improves soil health and livestock comfort
Whitten et al., 2019	Native grazing systems with strong plant diversity	Better thermal buffering capacity compared to low-diversity systems	Increased welfare scores in cattle	Natural capital in diverse systems supports livestock well-being

Methodology

Study Design and Data Collection

The experiment was conducted in three pasture coverage's: low, medium and high vegetation density in order to determine the adverse impact of plant composition in modifying the microclimate surroundings and livestock wellbeing. The vegetation diversity was measured in terms of the number of species richness, the Shannon Wiener diversity index, the percentage of the canopy cover, and the measures of vertical vegetation structure. These parameters gave a fully expressive characterization of ecological heterogeneity of each grazing unit. The calibrated digital environmental sensors were used to measure microclimate variables, such as surface temperature, ambient air temperature, relative humidity, wind speed and soil moisture, which were measured at regular positions at each plot. The physiological indicators measured using direct observation and non-invasive measurement equipment to determine the response of livestock included respiration rate, body temperature, and the duration of grazing in cattle and small ruminants. The general methodological scheme is presented in Figure 2, which shows the sequential way of processing the field data through model-based thermal comfort prediction processing.

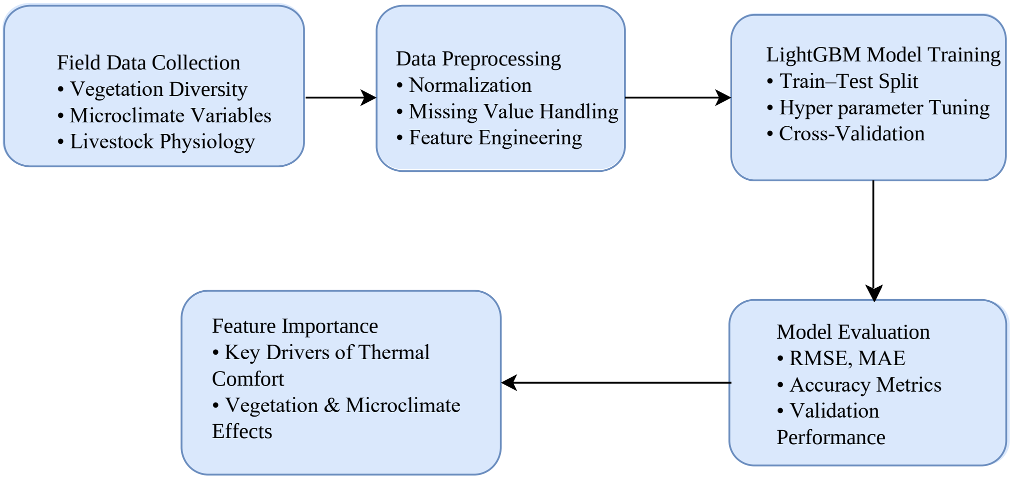

Figure 2: LightGBM Modeling Workflow Diagram

Data Processing and Feature Development

The variables on the environment, vegetation and livestock were incorporated into one analysis system. Before modelling, the data were subjected to preprocessing following steps which included consistency cheques, imputation of missing values by either mean or median, and normalisation of continuous data to make sure that the variables were normally scaled. The composite variables like the Thermal Comfort Index (TCI) and the heat-stress categories were calculated using the known physiological threshold concerning livestock species. The scores of vegetation diversity and indicators of microclimate were further normalised to increase the comparability across the periods of the sampling. More predictors with adjusted feature engineering like canopy ratio temperature, soil-moisture adjusted heat load and shade availability indices were obtained.

LightGBM Modeling Framework

LightGBM Framework LightGBM was created to determine the most important environmental and vegetation aspects that affect the thermal comfort of livestock. To guarantee an unbiased assessment, the data set was divided into training (70), testing (30) data set. The optimization of model hyper parameters, such as learning rate, maximum tree depth, the number of leaves, and fraction of features was done using k-fold cross-validation to improve the predictive performance. LightGBM was chosen as an efficient model in dealing with nonlinear interactions, but also its high performance in ecological datasets having mixed forms of variables. Regression measures like Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used to determine the accuracy and reliability of each model with different measures of success and metrics of classification, where categorical levels of heat-stress were to be predicted. The idea of the feature importance was conducted to identify which vegetation and microclimate factors had the strongest effect on the thermal comfort of livestock and to provide suggestions regarding the ecological management and pasture design with welfare in mind.

Results and Discussion

Influence of Vegetation Diversity on Microclimate

The findings proved that vegetation diversity significantly affected the microclimatic situation of grazing pastures. The plots with high-diversity always had significantly lower temperature on the surface due to the cooling effect of a greater canopy cover and higher vegetation density. The content of soil moisture also received significant advancement in these locations a factor that indicates improved water retention, because of the elevated organic contents and low rates of evapotranspiration. Conversely, the low-diversity pastures were characterised by greater range of temperature shifts and an increase in moisture loss and were therefore more vulnerable to heat accumulation in the hottest time of the day. Such results concur with previous research that focuses on the importance of the vegetation composition in altering the microclimatic patterns in the rangeland ecosystems. The differences in microclimate across the levels of diversity, which have been summarised, are shown in (Table 2).

Livestock Physiological and Behavioral Responses

There was a strong response of livestock to the microclimatic differences in pasture types. Animals grazing in high diversity plots experienced low rates of respiration and body temperatures and extended periods of grazing, which are signs of reduced heat stress and enhanced thermal comfort. Reduced shade-seeking behaviour and restless movements in these environments were also observed indicating that under cooler conditions animals could resort to normal grazing behaviour without having to go through thermal stress. In contrast, the livestock areas that contained low diversity did possess physiological stress scars such as increased respiration rate and reduced grazing duration. These results are consistent with the existing literature that vegetative shading and regulated microclimates are found to have a critical impact in reducing heat-stress to grazing animals.

LightGBM Model Performance and Key Drivers

The LightGBM model had a good performance in forecasting livestock thermal comfort with respect to vegetation and environmental predictors. The results of the model and its accuracy and low error measures were used to ensure that the model is applicable in modelling nonlinear and multidimensional interaction in grazing landscapes. The analysis of the feature importance showed that the most significant predictors of the level of heat-stress in livestock include canopy cover, the temperature of the soil during the day, the extent of soil moisture, and the vegetation diversity index. It is worth noting that the highest contributors were canopy cover that supports its primary function of offering thermal buffering. It also became clear in the model that the vegetation-based enhancement in microclimate, especially, lowering the surface temperatures and increasing the soil moisture directly corresponded to the improved livestock physiological state. The results favour the fact that machine learning tools can be used to appreciate ecological processes and inform sustainable pasture design.

Ecological and Management Implications

The combination of the vegetation diversity analysis, microclimate observation, and the machine learning analysis clearly indicates that the diverse pastures can be considered efficient nature-style solutions to livestock welfare enhancement. High-diversity pastures decrease the heat-stress load and enable animals to be able to graze optimally by the creation of cooler, more stable microhabitats. These environmental advantages ensure higher system resilience especially with commensuration climatic variability. The LightGBM outcomes also point out which vegetation features are most useful to thermo control to provide applicable recommendations in such topics as climate-resistant grazing areas. As one of the main priorities of management practises of producers who want to optimise the material comfort of livestock, its welfare, and long-term manageability of pastures, the enhancement of plant diversity should be an issue of concern.

Table 2: Microclimate Characteristics across Low-, Medium-, and High-Diversity Pastures

Microclimate Variable	**Low-Diversity Pasture**	**Medium-Diversity Pasture**	**High-Diversity Pasture**	**Ecological Interpretation**
Surface Temperature (°C)	Highest (34–38°C)	Moderate (30–33°C)	Lowest (26–29°C)	Dense vegetation reduces heat absorption and enhances shading.
Soil Moisture (%)	Low (8–12%)	Moderate (13–17%)	High (18–24%)	Increased ground cover improves water retention and reduces evaporation.
Relative Humidity (%)	Low stability; fluctuating	Moderate stability	High stability (more consistent)	Vegetation density buffers humidity variability.
Canopy Shade (%)	Minimal (5–10%)	Moderate (20–35%)	High (40–60%)	More diverse vegetation increases shading and thermal buffering.
Wind Speed (m/s)	Higher due to open exposure	Moderate	Lower due to vegetation obstruction	Vegetation structure reduces wind speed and prevents heat redistribution.

Future Research

Subsequent studies and studies are needed to expand on the results of the identified study by introducing the concept of long-term and multi-seasonal monitoring to better comprehend how the change in time and dynamics of vegetation affect the microclimatic stability and thermal comfort of livestock. More accurate detection of vegetation heterogeneity and its effects on the microclimate of diverse grazing landscapes would be made possible by monitoring and measuring variability of vegetation at higher spatial scales through the integration of more advanced remote-sensing instruments, including UAV-based multispectral imagery, LiDAR-derived measures of canopy structure, and high-resolution thermal imaging. The modelling framework could be further enhanced by adding hybrid deep-learning models, ensemble ecological, and spatiotemporal prediction algorithms, which can further enhance the precision of heat-stress situations forecasting in the changing climate conditions. Besides, this study should be extended to diverse ecological contexts, stock species, and regimes to contribute to the increased credibility of the findings and give more comprehensive information on how vegetation-based nature-based solutions supply livestock production with climate resilience. The incorporation of the animal behaviour sensors, GPS tracking and the real-time monitoring of the microclimate are also learnable by future research on the basis of which automated decision-support tools to be implemented in the management of pasture sustainability should be created.

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Conclusion

The paper is a good indicator that pasture vegetation diversity is an important aspect of controlling micro climatic effects as well as promoting the overall environmental comfort of grazing animals. The high-diversity pastures appeared to provide cooler microclimates, worked to keep the soil moist and provide more canopy cover all of which helped to alleviate symptoms of heat-stress in cattle and small ruminants. Those enhanced environmental situations favoured more stable and effective grazing patterns, which are associated with improved physiological and welfare conditions in the animals testified to a variety of vegetation structures. The use of the LightGBM model also exhibited the ability of machine learning to detect and measure the most important environmental factors that affect the thermal comfort of livestock, where the vegetation diversity, canopy cover, surface temperature, and soil moisture were identified as the most important predictors. Taken together, the results indicate that increasing the variety of plant communities should be an environmental protection consideration that will boost the resilience of pasture-based livestock systems. This study will add information to ecological research by combining both the theoretical foundations of ecological concepts and the practical modelling of data to create a sustainable climate responsive form of grazing management that can enhance animal well-being in a growing range of environmental conditions.

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