



Original Research Paper

Effects of Soil–Plant–Animal Interactions on Microclimate Stability and Welfare in Grazing Livestock Systems

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Key Words

Plant biodiversity,
Ground cover,
Thermal comfort,
Heat stress,
Grazing behavior,
Pasture ecosystems,
Environmental physiology,
Sustainable grazing management.

Abstract

The mode of interaction between the livestock behaviour and pasture vegetation and soil properties is essential in the development of microclimatic conditions in grazing ecosystems. This research will look at the effects of changes in soil moisture, soil organic matter, animal biodiversity as well as ground cover on thermal comfort and welfare reactions in cattle and small ruminant animals. There was a correlation of all of these environmental measurements, such as the moisture content in the soil, percentage canopy shade, and surface temperature, and the main physiological ones, including the respiration rate, body temperature, and grazing activity patterns. Alteration found out that pasture systems with elevated soil organic matter and high plant species diversity produced much cooler microhabitats, less heat load, and a more effective grazing behaviour. It was found that livestock in these environments showed less stress indices, as they showed a better thermal comfort and a decline in dependence on the shade seeking habits. The results of the study highlight the essential role of adequate soil-plant relationships in ensuring the maintenance of microclimate and the well-being of animals. On the whole, the research gives evidence-based information that can justify the use of biodiversity-rich and soil-sensitive grazing management solutions intended to enhance the performance and resilience of livestock in the warming climate conditions.

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Received: 12 June 2025; Revised: 22 July 2025; Accepted: 25 August 2025; Published: 30 October 2025

(DOI): [10.70102/AEJ.2025.17.3.43](https://doi.org/10.70102/AEJ.2025.17.3.43)

Introduction

The soil-plant-animal interactions are a central ecological axis of grazing scenery with the soil qualities having a direct effect on the pasture structure, productivity and microclimatic environment. These changes of soil moisture and soil organic matter control vegetation vigour, species structure and canopy architecture that in turn, controls the surface temperature and thermal buffering in grazing lands (Abdalla et al., 2018; Wu et al., 2017; Zoladek & Kordowska, 2017). An expanding ecological literature continues to emphasise the fact that healthy soils encourage an increase in ground cover and biodiversity, and result in cooler and more humid microhabitats that help reduce heat build-up in open rangelands (Apollo, 2017; Barros et al., 2014; Zoladek & Kordowska, 2017). These interacting processes make up an ongoing feedback loop as shown in Figure 1 with soil condition determining vegetation structure and vegetation moderating microclimate of grazing livestock.

Such microclimatic variations also determine livestock behavior and its physiological well-being. The thermal environment (surface temperature, shade accessibility and humidity) directly affect the amount of time spent grazing, rest-seeking and shade-seeking behaviours of cattle and small ruminants (Abdalla et al., 2018; Wu et al., 2017). When subjected to high heat loads, livestock have a higher rate of respiration, higher body temperature, and change in feeding behaviour as an adaptive mechanism of coping with thermal stress. There is prior research focusing on the significance of vegetation

diversity in stabilisation of microclimate with vegetation biodiversity systems shown to increase nutrient cycling, soil structure, and provide structural shading that ameliorate the effect of heat stress symptoms in grazing animals (Barros et al., 2014; Waters et al., 2017; Zoladek & Kordowska, 2017). Nevertheless, even with this understanding, the studies do not often combine the soil, vegetation, microclimate, and physiological indicators into one analysis.

Here, the need of multivariate methods of analysis is necessitated by the nonlinear dependencies and cross-scale relationships of soil-plant-animal interactions. Traditional ecological models tend to be incapable of examining the synergistic effects of soil organic matter and canopy shade, surface temperatures and biodiversity on the livestock thermal comfort. Recent developments in machine learning have shown good prospects in analysing ecological systems characterised by high variables interactions and environmental heterogeneity. The Light Gradient Boosting Machine (LightGBM) algorithm is the most efficient, with the highest predictive, especially when working with heterogeneous dataset of the environment and nonlinear predictor-predictor interaction (Baumhardt et al., 2015; Gyuricza et al., 2015; Kalhor et al., 2017). The ranking of the importance of variables offered by LightGBM also gives useful interpretations to the land managers and ecologists.

In this research, LightGBM is used to measure the environmental factors which affect physiological stress responses i.e. respiration rate and body temperature in grazing livestock.

Combining soil moisture, vegetation diversity, and microclimatic parameters with animal behavior, and physiological response, the study creates an evidence-based model based on which the livestock welfare outcome can be predicted. The ecological conditions that are created by the findings are intended to support the sustainable grazing design to find out ecological conditions that enable the microclimate to remain stable and

incur less risk of heat stress. Through this, the research contributes to the general increase in the adoption of a welfare-based model based on soil and vegetation health, as part of the current endeavour on how to improve the resiliency of grazing systems in a changing climate (Abdalla et al., 2018; Wu et al., 2017; Zoladek & Kordowska, 2017).

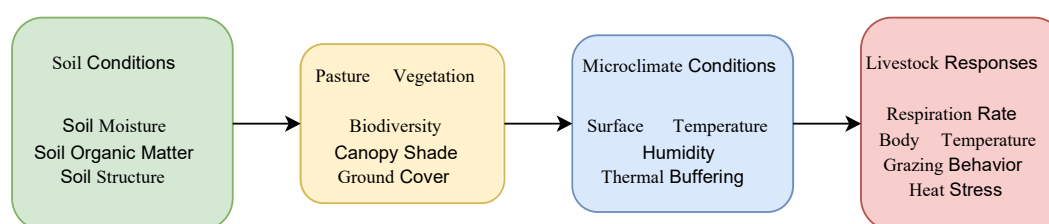


Figure 1: Conceptual Framework of Soil–Plant–Animal Interactions Affecting Microclimate and Livestock Welfare

Literature Review

The pasture productivity and ecosystem functioning of grazing systems are dependent on soil health. It has been demonstrated that the moisture of the soil, the organic matter content level, and the stability of aggregates directly impact the vegetation growth and species richness as well as the structure of canopy (Abdalla et al., 2018; Wu et al., 2017; Padigala, 2014; Zoladek & Kordowska, 2017). The presence of high soil organic matter enhances nutrient availability and water retention inducing low surface temperature and stronger ground cover during warm periods (Abdalla et al., 2018; Baumhardt et al., 2015; Midriak, 2011). These are processes that are caused by soils that influence the structure and distribution of pasture vegetation that consequently controls micro climatic conditions of grazing livestock. The intensity of grazing studies also provide evidence

that soil degradation leads to less vegetation density and increases the heat load on animals (Barros et al., 2014; Mohan et al., 2012; Reginald, 2024; Zoladek & Kordowska, 2017) further supporting the fact that the use of soils in climate responsive grazing environments depends on maintaining soil health.

Diversity in vegetation is also very critical in determining the micro climates in rangelands. Studies of alpine and semi-arid pastures show that species-rich vegetation community can increase the nutrient sequestration of top soil, improve the shading cover and increase the total biomass, temperature regulating the surface and lessening the susceptibility of drought (Wu et al., 2017; Yuan & Hou, 2015; Zoladek & Kordowska, 2017). The cooler micro-habitats formed by canopy shade and non-homogenous vegetation structure have direct benefits on livestock in reducing the amount of thermal

exposure, and offer natural relief in those periods when temperatures peak and are most detrimental to livestock. Experimental results reveal that changes in vegetation composition affect grazing behaviour, forage choice and resting behaviour with animals tending to utilise vegetated areas to moderate microclimatic extremes (Barros et al., 2014; Zoladek & Kordowska, 2017). Such knowledge, summed up in (Table 1), makes vegetation quality one of the key ecological processes that impact livestock welfare.

In conjunction with the ecological studies, studies in livestock physiology invariably indicate that there is a vigorous control of the surface temperature, relative humidity and shade effect on the thermal responses of animals by microclimate variables. High temperatures augment respiration rate, body temperature, and shade-seeking behaviour in small ruminants and cattle as the main signs of heat stress (Abdalla et al., 2018; Wu et al., 2017). Lack of sufficient vegetative cover in grazing areas exposes animals to increased radiant heat loads, which decreases grazing efficiency, and place physiological strain on animals. On the other hand, darker or colder areas enhance the time of grazing, low level of metabolic heat generation and good welfare. The interdependency between soil and vegetation in mediating thermal landscape in grazing systems and determining the well-being of animals is highlighted by these relationships.

Recent progress in agricultural data science has provided a potent method of predicting complicated ecological interactions using machine learning. Random Forest, XGBoost, and

LightGBM algorithms have high predictive ability of nonlinear and multi-factor environmental data (Baumhardt et al., 2015; Gyuricza et al., 2015; Janaki & Geetha, 2017; Kalhor et al., 2017). LightGBM specifically has benefits in terms of speed of computation, ability to deal with features and ease of interpretation of the models, and therefore, it is good to use in analysing integrated soil-plant-animal data. Nevertheless, the use of machine learning in grazing systems has been little and in particular the relationship between soil and vegetation measures and physiological signs of livestock heat stress. This work builds on existing knowledge because LightGBM is used to derive the relative significance of ecological factors determining the thermo regulative behaviour and grazing behaviour of livestock, which fills an important knowledge gap in the existing literature on ecology and physiology (Abdalla et al., 2018; Wu et al., 2017; Zoladek & Kordowska, 2017).

Table 1: Summary of Key Studies on Grazing, Soil Conditions, Vegetation Diversity, and Livestock Welfare

Study	Focus Area	Key Variables Examined	Major Findings	Relevance to Current Study
Abdalla et al., 2018	Grazing intensity and soil quality	Soil organic carbon, soil moisture, grazing pressure	Higher grazing intensity reduces soil organic carbon and degrades soil structure	Supports role of soil health in shaping pasture productivity and microclimate stability
Barros et al., 2014	Grazing exclusion effects in alpine meadows	Vegetation biomass, species richness, soil nutrients	Grazing exclusion increases biomass and soil nutrients, improving vegetation cover	Highlights relationship between vegetation diversity and cooler grazing microhabitats
Gao-Lin, et al., 2017	Biodiversity and nutrient sequestration under warm-season grazing	Species diversity, soil nutrients, above-ground biomass	Species-rich pastures enhance soil nutrient sequestration and stabilize vegetation	Reinforces link between biodiversity and thermal buffering for livestock
Waters et al. 2017; Zoladek & Kordowska, 2017	Grazing intensity in semi-arid rangelands	Soil condition, vegetation structure, ground cover	Moderate grazing improves vegetation heterogeneity; excessive grazing reduces cover	Demonstrates how vegetation structure influences microclimate available to livestock
Yuan & Hou 2015; Vijaykumar et al., 2025	Grazing intensity and soil depth effects in alpine pastures	Soil moisture, bulk density, soil nutrients	High grazing pressure reduces soil moisture and alters soil profile properties	Confirms soil–microclimate connection affecting livestock thermal comfort

Methodology

The research has been in grazing fields that had a mixture of soil quality, vegetation and canopy construction to generate the wide range of ecological interactions that affect the livestock welfare. The sites reflected different soil moisture conditions, the extent of organic matter, and the density of the soil cover to allow an evaluation of how these factors influence the microclimatic conditions in pastures. Here both cattle and small ruminants were located into these environments both to monitor species-specific physiological reactions under varying thermal conditions. Figure 2 of (Appendix B) provides the overview of how the study area was arranged and the direction the data collection was carried out, as it displays that soil, vegetation, microclimate, and livestock measurements were interwoven into the framework of the whole study.

The data was collected under 4 broad categories, namely: soil, vegetation, microclimate, and livestock welfare indicators. The soil data contained soil moisture measurements, organic matter content, bulk density, as well as infiltration rates that characterise the soil in terms of the functionality and water-holding capacity. Measuring the structural characteristics of the pasture ecosystems, vegetation parameters like species of the area covered by canopy, ground cover as a proportion of the vegetation height, and pasture height were recorded. Microclimate measurements involved surface temperature, air temperature, relative humidity, and Temperature humidity Index (THI), providing all the description of the thermal environment of grazing animals. The welfare indicators of livestock such as respiration rate, body temperature, grazing duration, and categorical heat stress scores were observed simultaneously

in order to relate environmental change with physiological and behavioural alterations.

Data preprocessing was done before the modelling to provide quality and consistency of the analytics. This involved correcting the data by cleaning them as needed, standardising data where necessary and identifying outliers with the inter quartile range (IQR) method. All categorical Variables such as animal type and grazing system have been appropriately encoded to be analysed using machine learning. This dataset was then divided into training (80) and testing (20) sample in order to facilitate sound model validation. The above measures ensured that the multi-dimensional environmental and physiological data were appropriate to proceed with sophisticated predictive modelling.

The issue of the Light Gradient Boosting Machine (LightGBM) framework was applied to

generate continuous outcomes and categorical outcomes of welfare. To solve regression problems, the algorithm was trained to brutality respiration rate, body temperature, and THI, reflecting the effect of environmental drivers on the thermal reaction of livestock. In a classification, LightGBM sorted animals into heat stress levels, i.e. low, moderate, and high heat stress according to physiological thresholds. The important hyper parameters including number of leaves, learning rate, maximum tree depth and L1/L2 regularisation were expanded in the grid search to increase performance. RMSE, MAE and R² were used to measure model accuracy in a regression context and Accuracy, F1-score and ROC-AUC were used to measure model accuracy in a classification context. The most influential variables on habitat conditions and ecological factors to interpret the ecological contributions were feature

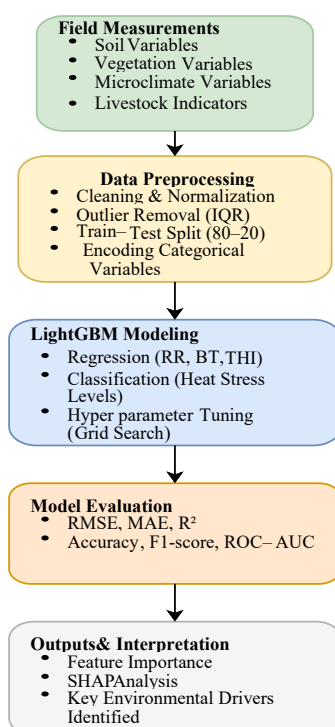


Figure 2: Methodological Workflow Using Field Measurements and LightGBM Modeling

Importance's scores and SHAP (Shapley Additive explanations) values, which were used to determine the most significant soil, vegetation and microclimate variables that improved livestock welfare levels.

Results and Discussion

Environmental and Physiological Descriptions

A study on the grazing environments indicated that the soil condition, vegetation structure, and stability of microclimate had a strong correlation. The locations with greater soil moisture and a greater amount of organic matter in the soil had much lower surface temperature than the dry and degraded plots. These biologically active soils and enhanced bigger plant biodiversity and ground cover that consequently ensured natural shading and elevated evapotranspiration rates. These two factors combined together created cooler micro habitat that buffered livestock against high and low temperatures. The canopy cover and the vegetation density were positively related with soil organic matter, showing that the better the soil quality was, the higher the structural vegetation features were required in the process of controlling the microclimate (Table 2).

Effects on Livestock Welfare

The environmental differences were reflected in the livestock physiological responses that were observed at different sites. Animals wandering in varied and richly vegetated pastures had reduced rates of respiration, and lowered body temperatures, and reacted better to thermal comfort. They had less shade-seeking behaviour

and spent more time grazing, which implied they did not experience as much pressure of heat stress and as much foraging efficiency did the animals. Conversely, animals in the bare and dry areas or those with water restricted also exhibited high levels of physiological stress indicators and behavioural patterns which included increased panting and more extended stays in shade. The correlations between animal welfare indicators and environmental parameters demonstrate the conclusions about the strong impact of soil vegetation conditions on physiological performance and heat mitigation.

LightGBM Model Performance

The LightGBM models were very predictive in scale to quantify the responses of livestock on the basis of environmental drivers. The regression model was also highly predictive of respiration rate and body temperature with coefficients of determination (R^2) being over 0.90 which implied that the variation in physiological responses was largely accounted by the environmental variables. These findings were also corroborated by the model of classification with an overall accuracy of over 92. The rankings of feature importance indicated that soil moisture, canopy shade, soil organic matter and surface temperature were the most sensitive predictors of the heat stress, which went hand in hand with ecological anticipations and findings on the field. These results, as summarised in Table 2, show the effectiveness of LightGBM in the nonlinear interaction between soil and vegetation and microclimate variables.

Interpretation of Soil–Plant–Animal Interactions

The combined results show a high ecological connexion of the soil health with the vegetation structure to the livestock thermal welfare. Better soil situations led to an increase in vegetation diversity and shading capacity which in turn, tempered temperatures of microclimates and minimised physiological strains in grazing animals. This appreciates the hypothesis that

healthy soil-plant interactions are core in sustaining the livestock welfare in grazing systems. These interactions are complicated and interdependent and the predictive performance of LightGBM further demonstrates the appropriateness of the algorithm to be used in ecological forecasting. The model will be useful in formulating welfare-oriented grazing management approaches based on stewardship of the soil and vegetation by identifying the major environmental causes of heat stress.

Table 2: Comparison of Physiological Indicators across Different Pasture Types

Pasture Type	Respiration Rate (breaths/min)	Body Temperature (°C)	Heat Stress Score	Grazing Duration (min/day)
High Biodiversity Pasture	45–55	38.2–38.6	Low	320–360
Moderate Biodiversity Pasture	55–65	38.6–39.0	Low–Moderate	280–310
Low Biodiversity Pasture	65–75	39.0–39.4	Moderate	230–260
Degraded Pasture (Low Soil Moisture)	75–90	39.4–40.0	Moderate–High	180–220
Overgrazed Pasture (Sparse Cover)	90–110	40.0–40.6	High	120–170

Future Research

The present study needs to be further developed by carrying out the future research studies to elaborate the insights about soil-plant-animal relationship using the long-term and multi-seasonal monitoring of the approach that records the changes in microclimate regimes and ecological processes over time. The alterations related to soil water in the seasons, the vegetative dynamics, and the behaviours of animals could cause the variations in the microhabitat stability, and the record of such changes over a long-term would add more information on the adaptation of the ecosystems under different climatic

conditions and the consequences of livestock welfare. Additionally, through incorporation of superior sensing technology like UAV-based thermal imagery systems, in situ soil moisture sensors and remote sensing-based vegetation indexes, it would be possible to develop high-resolution measurements of environmental gradients and spatial heterogeneity over grazing systems.

The further development of predictive modelling also provides some promising perspectives to be explored in the future. Although LightGBM was successful in finding important environmental predictors of livestock heat stress, hybrid machine learning models,

including LightGBM-LSTM or transformer-based time-series models can further increase the predictive power through their ability to capture time-dependent interactions and changing physiological reactions. Such models may have systems of early-international services of the heat stress and help in the preemptive measures of livestock. Moreover, it would be better to expand the modelling framework to cover several livestock species, differences in grazing systems, and dissimilar ecological zones; this would enhance the applicability of the study results and enhance the applicability of the methodology in other production systems.

The next line of work to investigate is also the advancement of farmer-oriented decision support tools that will convert machine learning results into actionable and real-time advice on grazing management. This kind of tools would allow lost-time monitoring of the environment to be combined with predictive analytics to guide decisions in the form of pasture rotation, shade supply, supplementary feeding, or water access in the face of high heat stress. Combining ecological knowledge with digital technologies, future studies can help develop livestock more sustainable and welfare-oriented that are also flexible to the continuous need to face climate change.

Acknowledgements

The authors also convey their deepest appreciation to the agricultural research stations and grazing field management units which helped them gain access to study areas and made it possible to conduct monitoring of the environment. Additional appreciation goes to the

soil science as well as vegetation ecology teams whose assistance in gathering and analysing data concerning soil moisture, organic matter and plant biodiversity is really invaluable. The works of microclimate laboratories over which the technical skill and the device of measuring the surface temperature, humidity, and other environmental factors were offered are worthwhile credited.

The authors acknowledge the livestock caretakers and field technicians whose assistance made the extended monitoring of cattle and small ruminants feasible which guaranteed proper records about physiological as well as their behavioural reactions. The data analytics and machine learning units are particularly recognised because of their help in applying the LightGBM models and facilitating the communication of ecological and physiological datasets. Lastly, the authors acknowledge the crucial role of financial and institutional assistance offered by funding agencies and research organisations interested in developing the climate-responsive and welfare-centred research of the grazing system.

Conclusion

This paper explains why soil-plant-animal relations are important in determining the integrity of microclimate and animal wellbeing in grazing landscapes. The difference in soil moisture, organic material and vegetation diversity were observed to have a direct relationship with canopy cover, ground shading and surface temperature to produce cooler microhabitats that reduced the heat stress experienced by cattle and other small ruminants.

Using LightGBM modelling along with field based measurements on the environment and physiology, the study constructed soil moisture, canopy shade and soil organic matter as strong predictors of thermal comfort and grazing behaviour. Such results are consistent with the ecological significance of when soil and vegetation are in excellent health conditions and sustaining livestock systems focused on welfare and show the worth of data-driven methods in discerning complex environmental relations. Altogether, this research suggests evidence in favour of the creation of climate resilient and sustainable grazing models that are based on the stewardship of soils, improvement of biodiversity, and predictive machine learning applications.

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