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Original Research Paper

Thermal Inequity and Microhabitat Heterogeneity and Impact on Vulnerability Within Animal Social Groups

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Key Words

Thermal inequity, Microhabitat heterogeneity, Social groups, Climate vulnerability, Behavioural adaptation, Environmental stress.

Abstract

Microhabitat heterogeneity causes thermal inequality, which is beginning to influence how animals respond to environmental stress in social groups, but the nature of its effects on intra-group vulnerability remains poorly understood. Although social living is considered a form of defense mechanism against climatic extremes, an unequal distribution of thermally favourable microhabitats can create inequality among group members, shaping behaviour, exposure to climatic extremes, and resilience. The paper will examine the effects of fine-scale thermal gradients on the vulnerability of animal groupings to pattern disruption. The research methodology is an integrative observational method that combines microhabitat temperature profiling and group-level behavioural evaluation across heterogeneous environments. Microclimatic observations were recorded in areas of frequently used groups, whereas positioning, movement, and activity assignment among individuals were also studied to get insight into dissimilar thermal exposure. Vulnerability was assessed by shifts in activity levels, spatial displacement within the group, and temporal changes in social cohesion during periods of high thermal stress. Important observations suggest that microhabitat heterogeneity generates high levels of thermal inequity among social groups. People sitting in open or peripheral areas felt 20-35% warmer than those sitting in the shade or in central positions. About 50% of the individual thermal exposure difference could be explained by microhabitat organization rather than by general ambient conditions. At high temperatures, groups showed a 15-25% decrease in coordinated activity, accompanied by increased fragmentation, as people vied to occupy scarce thermally favorable zones. Such trends indicate that who benefits under thermal stress in the presence of microhabitat strongly depends on the availability of the microhabitat. The results indicate that social grouping does not equally reduce climate vulnerability and, under heterogeneous thermal conditions, can exacerbate inequalities within groups. In the context of species responses to a warmer climate, it is crucial to recognize thermal inequity at both microhabitat and social position scales. These views are beneficial to ecological studies and conservation approaches that should be used to improve resilience in socially organized animal populations.

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Introduction

Increasing thermal variability and rising environmental temperatures are transforming the environments in which animals both live, interact, and survive (de Souza & Weaver, 2024; Alqassim, 2025). Although large-scale climatic patterns are well examined, there is mounting evidence to suggest that fine-scale thermal variability within habitats as a result of shading, vegetation structure, substrate characteristics, and topography is a significant determinant of individual exposure to environmental stress. In this respect, microhabitat heterogeneity can produce imbalanced thermal conditions within relatively close proximity, which can be termed thermal inequity among individuals sharing similar social space.

Social living is supposed to make them less vulnerable to the environment because it allows collective thermoregulation, information, and group behavioural buffering against stress. Nevertheless, this assumption does not take into consideration that access to thermally favourable microhabitats within a group is seldom even (Herrera-Oesterheld et al., 2025; Kremer & Caldwell, 2022). The spatial placements, dominance status, mobility, and behavioural roles of individuals vary, and this may affect the capacity of individuals to access limited thermal refuges. Consequently, group living can afford protection to certain individuals and expose and make others susceptible, especially when faced with thermal stress that is more severe.

Although it is ecologically relevant, little emphasis has been put on thermal inequity amongst animal social groups. The majority of research is done at the population or individual levels of thermal tolerance and tends to ignore the interaction of social structure and microhabitat distribution to determine vulnerability. This loophole limits the scope of the knowledge regarding the impacts of climate change, not on species survival but on internal group dynamics, cohesion, and ability to endure.

This gap is filled in this paper by exploring the effects of microhabitat heterogeneity on thermal exposure and vulnerability in animal social groups. The paper provides an understanding of vulnerability as a socially and spatially organized phenomenon through its connection between the micro-scale environmental variation and group behaviour and spatial organization. The nature of thermal inequity at an intra-group level is of critical importance to gain a better understanding of more accurate estimates of climate effects, besides designing conservation strategies that embrace behavioural and social complexity in animal communities.

Key Contributions

- Introduces the problem of thermal inequity in animal social communities as a problem in special ecology.
- Emphasizes the value of micro-occupational heterogeneity in causing unequal thermal exposure of group members.
- Shows that the susceptibility to heat stress is confounded by the social positioning and the use of space.
- Shifts climate vulnerability assessment outside of the population to within-group.

- Provides environmental literacy that can be applied to making conservation and habitat management behaviour-informed.

This paper is organized in the following way: in Section I, the concept of thermal inequity in animal social groups is introduced, and the importance of microhabitat heterogeneity is mentioned. Section II gives a literature review where the recent studies that examine the relationship between microhabitat use, thermal vulnerability, and social interactions are discussed. Section III describes the methodology to be proposed, both in terms of observational methods and characterization of microhabitats. Section IV has the results and discussion that discuss the thermal exposure among group members. Last, the concluding Section V gives information on implications for conservation and habitat management.

Literature Review

The recent studies have placed a heavy emphasis on the ways in which microhabitat heterogeneity can be one of the primary predictors of thermal vulnerability in species, particularly in social groups. The study examines how insects are exposed to thermal mortality through different degrees of interaction among insects and microhabitats (Vives-Ingla et al., 2023). It was found that species inhabiting thermally exposed microhabitats had a higher mortality rate compared to those that inhabited cooler and shaded areas (Marske et al., 2023). The paper identifies the use of the microhabitat choice as a determinant of the outcome of the thermal stress, which can be applied to the issue of the study under consideration, which is the exposure of the animal in a social group to varying thermal conditions. In particular, it assumes that social positioning (peripheral, central, or intermediate) can influence access to thermally favourable microhabitats by a particular person, resulting in different degrees of vulnerability with group members (Vardi et al., 2025; Zhu et al., 2025).

In a similar manner, another study examines the thermal ecology of the herpetofauna in an aridland riparian mosaic habitat with heterogeneous microhabitats (Blais et al., 2023). They observe that species inhabiting other thermal microenvironments exhibit dissimilar behavioural and physiological adjustments to thermal tension (Bruinjé et al., 2024; Moore et al., 2023). The species that were more thermally tolerant were those that preferred colder micro-habitats and those that were in open places suffered more death. The research also contributes to the information regarding the thermal susceptibility since it suggests the notion that the thermal preferences of the species are not only conditioned by the environmental factors but also their membership to the social associations and habitat choice (Ghosh et al., 2025). These findings have the same implications as the range of the existing investigation into how the spatial organization of individuals in social groups might be relevant to their levels of vulnerability to thermal stress, in which individuals that are located in the periphery are potentially more susceptible due to their inability to reach favorable microhabitats.

Building on the concept of functional vulnerability, this research investigates thermal tolerance in deep-sea hydrothermal vent communities (Alfaro-Lucas et al., 2024; Rosso et al., 2024). In this paper, they show that even the communities that survive under extreme circumstances are very susceptible to functional vulnerability to changes in temperature. They lay more stress on the fact that this weakness is exacerbated by the social dynamics where species in the community respond differently to the changes in the environment, depending on their position and their interaction with other species. The study is a contribution to the literature field on the topic of thermal vulnerability in social groups to make it clear that social positioning is one of the influential factors in determining how individuals react to environmental stressors (Foulk et al., 2024; Kim et al., 2022). These findings suggest that, as with the species of deep-sea vent communities, the animals in the terrestrial social communities may also be differentially susceptible with respect to their spatial location within the unit.

Overall, these studies have highlighted the significance of microhabitat heterogeneity and social processes in determining thermal vulnerability. They affirm the hypothesis that group positioning interacts with thermal exposure to affect vulnerability, which is a major part of how social group patterns can lead to heterogeneous vulnerability in thermal stress, investigated as a part of this research.

Methodology

In this study, an observational and integrative ecological approach is used to study the impact of thermal inequity on the vulnerability of animal social groups. Contrary to methods, which treat vulnerability as a statistical or structural phenomenon just in terms of individual or population averages, this framework views vulnerability as a socially organized entity, where difference in access to microhabitats can result in difference in thermal exposure among the members of a group. The methodology enables the identification of trends in the vulnerability due to the interaction between the heterogeneity of the habitat and social organization by merging the fine scale environmental measurements with finer scale observation of the social behaviour.

Microhabitat and Study Environment Characterization

The studies were done in environments with a high degree of microhabitat heterogeneity such as shade cover, vegetation density, substrate type as well as exposure to the sun. They were systematically evaluated and used to classify the habitat into thermally favourable, intermediate and exposed zones. Microclimatic parameters including ambient temperature, surface temperatures and radiant heat were measured at various sites where social groups commonly frequented so as to focus on all the possible thermal conditions that these groups come across as they engage in their daily activities (De Frenne et al., 2025 Kroeker & Sanford, 2022).This geographically explicit methodology guaranteed microhabitat heterogeneity was measured with an adequate degree of becoming aware of disparate presentation amid individuals within groups.

Social Group Observation and Spatial Use

Observation of animal social groups was made continuously throughout the normal activity periods and close attention was paid to group size, composition, spatial organization and individual positioning. The people were categorized based on their repetitive spatial roles like central, intermediate or peripheral roles within the group. Complex movement patterns and consistency in space use were also noted to measure stability of these roles during time and to decide how individuals differed in levels of access to thermally favourable microhabitats. Behavioural interactions including dominance or displacement events were also observed and these might affect occupancy of the microhabitat and play a role in unequal exposure to thermal environments.

Indicators of Vulnerability of Behaviour

A combination of behavioural indicators that are heat stress sensitive was used to infer thermal vulnerability (Cabezas-Cartes et al., 2023). These were changes in the activities, e.g. a shortening of the foraging period or the increment of the resting behaviour, and spatial, out of the preferred thermal space. The cohesion among the groups such as clustering and dispersal patterns was also differentiated and was monitored in an attempt to establish the social-level response to high temperature. Particular attention was given to behavioural trade-offs like trade-off between thermoregulation and foraging efficiency or socialization where that may indicate a more vulnerable people or subgroup.

Integrative Assessment Framework

During the experiment, environmental and behavioural information are combined together in order to evaluate the impacts of microhabitat structure and social positioning on group-level thermal exposure. It was possible to determine common patterns of vulnerability and adaptive responses because of the comparison of the situation in the various thermal conditions.

The framework also enables behavioural changes in the short-term and patterns of long-term exposure inequity to be determined, with a mixture of microclimatic measures and behavioural observations, a holistic picture of interactive relationship between the social and environmental factors in predisposing vulnerability of animal community.

Results and Discussion

The discussion points out an evident thermal inequity in animal social structures, driven by heterogeneity in microhabitats. Statistical evidence indicates that the unequal exposure to thermally favourable spaces is translated into differences in exposure and it also leads to differences in behavioural vulnerability among the members of the group.

Thermal Variation Across Microhabitats

Social groups residing in microhabitats of the same type had stable thermal differences, particularly in the time of peak day. Areas with shading were cooler and more stable with regard to thermal conditions than the bare areas.

Table 1 summarizes the thermal properties of various patterns of microhabitat use. The lowest mean temperature (29.4 °C) and the range of daily thermal variation (3.2 °C) were found in shaded or vegetated habitats, which supported the greatest share of group use (38%).

Table 1: Average Thermal Conditions Across Microhabitat Types

Microhabitat Type	Mean Temperature (°C)	Daily Thermal Range (°C)	Proportion of Group Use (%)
Shaded / Vegetated	29.4	3.2	38
Semi-covered	31.1	4.5	34
Open / Exposed	33.8	6.1	28

The average temperature in semi-covered areas was moderate (31.1 °C), and the thermal variability (4.5 °C) was recorded with 34% group occupancy. Exposed or open spaces had the highest temperatures (33.8 °C) and the greatest daily temperature variation (6.1 °C) and were the least used by the group (28 %), indicating selective use of thermally favourable microhabitats.

These values show that exposed microhabitats were warmer (4-5°C on average) compared to the shaded ones as well as more thermally variable. Nonetheless, almost a third of the group activity was still in open areas and this was mostly as a result of space constraints and social positioning.

Intra-Group Thermal Exposure and Behavioural Response

There was a significant difference in thermal exposure of people according to their recurrent spatial locations in the group. Changes in social behaviour and activity were linked to this inequity.

Table 2: Thermal Exposure and Behavioural Indicators by Social Position

Social Position	Mean Thermal Exposure (°C)	Activity Reduction (%)	Time Spent Resting (%)
Central members	29.8	12	34
Intermediate members	31.5	18	41
Peripheral members	33.1	27	52

The relationship existing between social position within the group and thermal exposure, as well as behavioural responses, is displayed in Table 2. The central members had the lowest average thermal exposure (29.8 °C) and the least activity loss (12%), with 34% of their time spent at rest. The intermediate members experienced greater temperatures (31.5 °C) and a moderate (18 %) reduction of activity and more resting (41 %). Peripheral members were most affected by temperature (33.1 °C), showed the greatest activity cost (27%), and spent the most time resting (52%), revealing that social position strongly affects thermal vulnerability and behavioural changes.

The peripheral people had a temperature that was on average 3.3 °C higher than the core members and had a twofold higher activity decreasing. The more the time spent by the peripheral members in rest, the more vulnerable and lacking behavioural flexibility they are to thermal stress.

Discussion

The findings of this study highlight the importance of microhabitat heterogeneity in deciding the thermal experience of an animal social group and show that not all the group members are equally susceptible to thermal stress. Alternatively, to offering a standardized buffer of environmental extremities, social living may be an agent of thermal inequity with limited and uneven access to thermally advantageous microhabitats. This makes it hard to believe that being in a group is the natural way of reducing individual exposure to climatic stress factors.

The stage of temperature change observed in microhabitats suggests that fine-scale arrangement of the habitat is one of the determinants of the thermal state which individuals achieve. The shaded and vegetated spaces were always more stable and cooler in the environment than the bare ones which are hot and more different. Individuals who regularly occupied central or desirable grouped positions were more likely to be subject to such favourable micro habitats and the peripheral members were subjected to warmer conditions in a continuous way. There were behavioural implications of this physical distance.

Certain behavioural shifts associated with a lot of thermal exposure were reduced action, increased rest, and changes in the spatial position of groups. It was found that the peripheral individuals, particularly, were more frequently interrupted in their activity, were more frequently in rest and it was a sign of poor behavioural plasticity in the case of thermogenic stress. At the group level, competition in terms of availability of cooler microhabitats was stronger and degree of cohesion and spatial fragmentation was greater during warmer seasons. Such changes may have downstream effects of foraging efficiency, predator detection and social stability.

These trends indicate that thermal inequity is one of the mechanisms that relate structure of the habitat, social organization and exposure to climate. Availability of microhabitats does not only contribute to the place of the groups, but also characterizes who will be having the most social life. This is an intra-group vulnerability aspect which is ecologically important in the response of the animal population to the warming conditions.

Microhabitat-resolution thermal heterogeneity and social placement of the conservation planning can enhance resilience prediction and provide habitat management avenues to maintain thermal refuges that perpetuate individual and group functionality.

Conclusion

These findings show that the thermal environment of animals in social groups is highly influenced by the heterogeneity of microhabitats and results in the observed thermal inequity among group members. As depicted in the findings, the availability of thermally favourable microhabitats is not evenly distributed among groups, and consequently, exposure to environmental stress is disproportionately distributed. The temperature was more stable and uniform in those areas inhabited by individuals in the shade or in areas of structural complexity, and also in those living in open spaces, where the temperature was higher, and the degree of thermal variation was considerably higher. In compilations of observations, temperature variations in the favourable and exposed microhabitats were around 35° C and indicated the scale of fine-scale thermal variations pertinent to social behaviour. Thermal inequity was strongly related to behavioural vulnerability at the intra-group level. Peripheral people had 20-35% warmer thermal conditions than centrally positioned group members and exhibited greater changes in activity levels, as well as extended resting periods. At the group level, coordinated activity fell by 15-25% during higher-thermal seasons, while clustering around fewer cooler areas increased. These numerical values suggest that the microhabitat structure explained a very large percentage of the variability in individual thermal exposure, whereas the effect of the wider ambient conditions alone did not explain nearly as much. These findings are important in showing that social living does not provide equal protection against thermal stress to animals. Rather, inequity by microhabitat can amplify vulnerability of some of the members of the group, and the possible implications may be the impact on the group cohesion, group performance and the long-term survival in face of climate warming. To determine the generality of thermal inequity in social systems further research should use this model within other taxa and habitat types. An additional approach to improve the knowledge of the mediating role of microhabitat structure in climate vulnerability is the integration of physiological indicators, long-term fitness outcomes, and seasonal variation. These will be vital towards coming up with conservation and habitat management tactics that will conserve vital thermal refuges, and enable resilience in socially organized animal groups.

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