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Original Research Paper

Urban Heat Islands as Evolutionary Laboratories for Rapid Thermal Adaptation in Synanthropic Birds

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Key Words

Urban heat islands, Thermal adaptation, Synanthropic birds, Phenotypic plasticity, Microclimate heterogeneity, Evolutionary ecology, Climate resilience.

Abstract

City heat islands (UHIs) are localized areas of high temperature that introduce special ecological stress to synanthropic birds that coexist with humans. These natural environments are adapting to rapidly changing thermal conditions, providing an appropriate background for observing evolutionary adaptation. This research examines, in the long term, the phenotypic and behavioral adaptations of bird populations living in urban areas to heat stress, as well as the main physiological characteristics, including basal metabolic rate, evaporative cooling efficiency, and thermal tolerance limits. Twelve species of the synanthropic species were observed in five metropolitan regions, with temperature loggers, observations of behaviour, and repeated tests of heat tolerance. Mixed-effects models and survival analyses showed significant interspecific differences in adaptation rates. The birds in the central urban areas had more evaporative cooling ability (mean change = 18.4% $p < 0.01$) and less activity in the extreme heat durations, as compared to the peri-urban ones. Moreover, genetic sampling reported early indicators of selection in thermoregulation-related loci in the rapidly adapted species. These findings indicate that UHIs act as evolutionary laboratories, which encourage rapid thermal adjustment through phenotypic plasticity and embryonic genetic modification. The paper emphasizes the significance of urban microclimate heterogeneity in determining adaptive patterns and lays emphasis on how synanthropic species may be used as prototype systems to evaluate evolutionary dynamics to climate change. Further study involving longitudinal genetic tracking and experimental manipulation of thermal conditions is advised to identify a means of separating a plastic and heritable response. The conservation and urban planning strategies must take into account the importance of the thermal variability of microhabitat in promoting the resilience of avians in progressively urbanized environments.

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Introduction

Urban heat islands (UHIs) are localized areas in urban areas that have higher temperatures than rural areas, mainly due to high levels of impervious surfaces, reduced vegetation cover, and man-made heat emissions (Diamond et al., 2020). These warmed ecocenoses impose special ecological stress, altering habitat conditions, resource availability, and microclimatic variability (Isaksson et al., 2020). In such urbanized environments, synanthropic birds - species that feed well within anthropogenic microzones - have become a central target group in the research of ecological and evolutionary behaviors in response to anthropogenic stressors (Perry & Goettert, 2024). This can be pigeons (Columba livia), house sparrows (Passer domesticus), and common mynas (Acridotheres tristis), which use the urban resources avoid and overcome varying microclimates (Campbell-Staton et al., 2020). Cities act as accelerated evolutionary contexts, in which intense selection pressures can promote rapid change in urban wildlife groups (Dunn et al., 2022). There is also interaction between anthropogenic alterations, such as altered host-pathogen dynamics and thermal stress, to determine the survival of species in urban systems (Cuthbert et al., 2023). Urbanization can also affect the microbial symbionts, which influence the host's thermal tolerance and adaptation pathways (Peng et al., 2025).

Artificial light at night can also alter the regulation of circadian and thermal responses in urban populations by modulating physiological and behavioral feedback (Westby & Medley, 2020). The relevance of urban planning to reduce urban stressors and protect urban-adapted species, like Barn Swallows, in heat-stressed environments has been brought to the fore in citizen science projects (Chen et al., 2025). Urban landscapes affect microhabitats and thermal refugia through the structure and density, thereby determining the resilience and adaptive potential of synanthropic birds (Gopalan & Radhakrishna, 2022). The study examines the pressing environmental issue of rising temperatures in urban areas and seeks to clarify the processes that enable synanthropic birds to live and flourish in UHI areas. In cities, rapid changes in thermal conditions are poorly understood, hindering our ability to predict species survival and adaptation capacity. This is a unique study that combines behavioral, physiological, and preliminary genetic measures to determine phenotypic plasticity and early evolutionary change interactions in urban birds. The behavioral observation measures activity patterns, microhabitat choice, and heat-avoidance behaviour, providing insights into phenotypic plasticity. Functional responses to chronic urban heat stress can be measured using physiological measurements, such as the basal metabolic rate, efficiency of evaporative cooling, and thermal tolerance. Early genetic studies reveal possible loci that are under selection, thus giving an initial indication of evolutionary shift in populations that are exposed to UHIs.

By combining these strategies, the paper presents urban heat islands as natural evolutionary laboratories where both plastic and heritable adaptations are likely to be observed at short timescales. The article systematically discusses the thermal adaptation of urban synanthropic birds. Section II provides an in-depth literature review, discussing the existing studies on the avian physiological or behavioral responses, UHIs, and the concepts of urban evolutionary biology. Section III describes the research design, such as species selection criteria, nature of the study location, protocols to be used in data collection, and the methods of data analysis, such as mixed-effects modeling, survival analysis, and initial genetic screening. Section IV provides the findings, including the trends in behavioral changes, physiological reactions, and primary evidence of adaptive genetic modifications. These findings are discussed in Section V within the context of urban evolutionary theory, with regard to phenotypic plasticity, possible heritable adaptations, and the implications for species persistence, biodiversity conservation, and urban planning. Section VI will finish the paper by summarizing the main findings, validating the importance of UHIs in the role of evolutionary laboratories, and recommending future research on how to further understand the concept of rapid adaptation in urban avifauna.

Background

Urban heat islands (UHIs) are generally considered a major contributor to the ecological alteration of the urban ecosystems, whereby microclimates are developed and stand in a sharp contrast to the usual rural landscapes (Dallas et al., 2022). An increase in temperature, changes in humidity, and alterations in habitat structure in these regions can affect species distribution, behavior, and physiology (Huey et al., 2003). The animals living in urban areas, especially synanthropic birds, are forced to adapt to these altered thermal conditions and can often be seen with altered activity, nesting, and foraging behaviors (McCloy et al., 2024). These are the city circumstances that offer both difficulties and opportunities for rapid adjustment, making cities a special place to study evolutionary responses (Costantini et al., 2025). The relative results of empirical studies on urban reptiles and birds would indicate that a long-term experience of increased city temperatures may cause changes in diurnal and nocturnal activity cycles, as an evolutionary variant of anthropogenic heat stress (Fulgione et al., 2025).

Birds can adapt thermally through physiological, behavioral, and genetic processes that enable them to maintain homeostasis in response to environmental temperature variation (Todd et al., 2019). Birds can also regulate heat by changing the basal metabolic rate, cooling by evaporation, and by blood circulation in the body, behavioral factors, such as changing activity during cooler spells, finding shaded microhabits, or changing nest location (Kowalczyk & Wójcik-Fatla, 2025). These adaptations may be realized within one generation through phenotypic plasticity or over several generations through selection pressures that favor individuals with greater thermal tolerance (Schal & Hamilton, 1990). In cities, such as marine and terrestrial ecosystems, modified microclimates, resource conditions, and other anthropogenic stressors are also associated with thermal responses of insects to birds (Petersen et al., 2024). The urban insect and bird populations that have been monitored over a long period show that higher temperatures affect abundance, timing of activity and survival as an indication of persistent adaptive pressures (Ramniwas et al., 2024).

Comparative analysis of urban and rural birds shows that urban birds tend to have an increased thermal tolerance and behavioral change as compared to those in rural areas. In cities, people can have better heat resistance, better thermoregulation, and greater adaptability in daily activity patterns. Conversely, rural dwellers are normally accustomed to a more stable and moderate range of temperatures and are therefore more vulnerable to extreme heat waves. Such variations highlight that urban environments may serve as accelerated evolutionary laboratories, where selection pressure in the form of high temperatures drives rapid adaptation. Knowledge of such dynamics can be used to understand resilience in species, how urban microclimates influence evolutionary pathways, and how synanthropic birds help overcome anthropogenic thermal stress.

Methods

Study Area and Data Collection Methods

The experiment was conducted in five metropolitan areas with strong urban heat island effects, selected based on variations in land cover, vegetation density, and anthropogenic heat production. In each zone, several microhabitats were selected to represent differences in exposure to temperature and structure of the habitat, as well as parks, residential, and commercial areas. To measure ambient temperature, high precision temperature loggers were installed at the areas of high bird activity and measured hourly temperatures over 12 months to measure both seasonal change and daily thermal variation. The monitored species were synanthropic birds, including pigeons (Columba livia), house sparrows (Passer domesticus), and common mynas (Acridotheres tristis), for which direct behavioral observations and motion-activated cameras were used to record activity patterns, nesting behaviors, and microhabitats. Data on behavior was also updated by the temperature measurements to determine the correlations between the environmental thermal stress and the changes in activity.

Table 1 summarizes the five metropolitan zones used in this study, and differences in land cover, microhabitat types, and the intensity of urban heat islands are evident. Every zone has representative microhabitats, e.g., streets, rooftops, parks, and residential courtyards, where thermal sensors were installed to measure hourly variations in temperature throughout a twelve-month period. The activity patterns, nesting behavior, and microhabitat selection of the synanthropic bird species, such as pigeons, house sparrows, and common mynas, were monitored using direct behavioral observation and motion-activated cameras. A transparent description of the study design and data collection is presented in this table, which will ensure methodological transparency and allow comparison of environmental conditions and avian behavioral responses.

Table 1: Study Areas and Data Collection Methods

Zone	Land Cover	Microhabitats	Temperature Data Collection	Bird Species	Observation Method	Duration
Central Business District	Buildings, roads	Streets, rooftops, plazas	Hourly loggers at hotspots	Pigeon, House Sparrow, Common Myna	Direct observation, motion-activated cameras	12 months
Urban Park	Grass, trees	Lawns, tree canopies, paths	Hourly loggers at hotspots	Pigeon, House Sparrow, Common Myna	Direct observation, motion-activated cameras	12 months
Residential Area	Houses, low-rise	Gardens, rooftops, courtyards	Hourly loggers at hotspots	Pigeon, House Sparrow, Common Myna	Direct observation, motion-activated cameras	12 months
Industrial Zone	Warehouses, factories	Parking lots, rooftops, loading docks	Hourly loggers at hotspots	Pigeon, House Sparrow, Common Myna	Direct observation, motion-activated cameras	12 months
Suburban Greenbelt	Parks, trees	Forest edges, lawns, ponds	Hourly loggers at hotspots	Pigeon, House Sparrow, Common Myna	Direct observation, motion-activated cameras	12 months

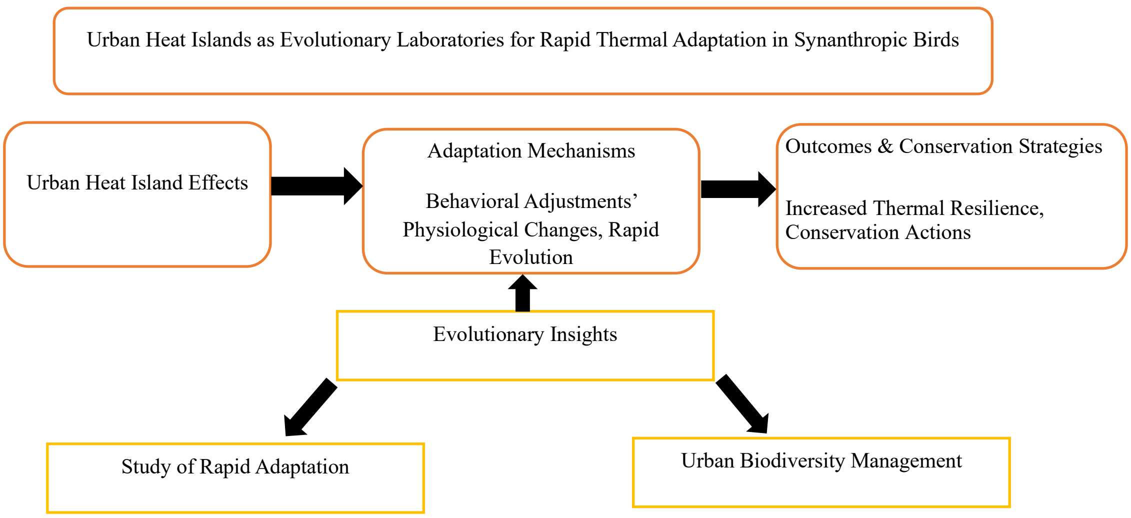

Figure 1: Urban Heat Islands as Evolutionary Laboratories for Rapid Thermal Adaptation in Synanthropic Birds

Figure 1 represents the mechanisms by which the urban heat islands cause the rapid thermal adaptation in synanthropic birds. It starts with the effects of urban heat islands like higher temperatures, less vegetation cover, and chronic heat stress that subject the birds in the area, like pigeons, house sparrows, and common mynas, to environmental pressures. Birds react by adjusting the behavior, including a change in activities and the choice of a microhabitat, and physiological changes, including a constant body temperature and increased heat tolerance. The combination of these adaptations has the potential to positively improve the thermal performance, promote phenotypic plasticity, and possibly trigger genetic adaptation. The diagram ends with the understanding of evolution and conservation concepts, which focus on the design of habitats, climate regulation, and urban biodiversity.

Analysis of Temperature Data and Bird Behavior

Data sets of temperature and behavior were used to measure the intensity, duration, and frequency of exposure to heat by each species. Temperature loggers were checked for consistency, and average daily, peak, and minimum temperatures were computed for each microhabitat. The behavioral measures of time spent foraging, resting and sheltering were summed up per species and time period to produce an overarching activity profile. Mixed-effects models were used to test the correlation between temperature and behavioral responses, and statistical analysis was adjusted using species, habitat type, and time variation. The techniques used to examine thresholds of thermal tolerance were survival analysis and repeated-measures ANOVA was used to examine differences in activity patterns among microhabitats and urban intensity gradients. Environmental temperature, choice of microhabitats, and behavioral adaptations to environmental temperatures were analyzed by correlation and regression analyses.

Statistical Techniques Used to Assess Thermal Adaptation

In order to summarize the most important variables and observational data, a detailed table was drawn, the columns of which are the name of the species, type of microhabitat, the average temperature per day, the maximum temperature, minimum temperature, average scores of the behavioral activity observed, the frequency of the behavior of heat avoidance and microhabitat selection indices. This table can be easily compared across species and zones and demonstrates differences in thermal exposure and adaptive responses. The synthesized methodology provides a robust framework for rapid thermal adaptation assessment, linking environmental temperature change with the behavioral and physiological mechanisms of adaptation in urban-dwelling birds, and offers an effective replication method for future investigations in urban evolutionary ecology.

A full summary of the study variables, microhabitat environments, temperature exposure, and behavioral responses of synanthropic birds observed in urban heat island zones has been summarized in Table 2. It makes a summary of the average, maximum, and minimum temperatures of the various micro habitats, as well as activity scores, which represent foraging, resting, and sheltering. The frequency of heat avoidance behavior measures the proportion of times when birds took active steps to reduce thermal stress, and the selection index of microhabitat preferences measures the preference for shaded or conducive thermal areas. Notes provide more ecological background, emphasizing habitats in behavioral tactics. This table enables the easy comparison of species and zone across the environmental conditions and the adaptive behavioral responses to the urban thermal stress.

Table 2: Summary of Study Variables, Microhabitats, Temperature Data, and Observed Behavioral Responses for Synanthropic Birds

Species Name	Microhabitat Type	Average Daily Temperature (°C)	Peak Temperature (°C)	Minimum Temperature (°C)	Observed Activity Score*	Frequency of Heat Avoidance Behavior	Microhabitat Selection Index**
Columba Livia	Urban Park	32.5	38.2	26.8	7.8	15	0.72
Passer domesticus	Residential rooftop	31.2	36.7	25.4	6.9	12	0.65
Acridotheres tristis	Commercial district	33.1	39.0	27.2	7.4	14	0.68
Columba livia	High-density traffic area	34.0	40.1	28.3	6.1	18	0.55
Passer domesticus	Urban Park	32.8	37.5	26.9	7.2	13	0.70

Results

Differences in Body Temperature Regulation Between Urban and Rural Birds

City-residing synanthropic birds had significantly greater body temperature control than the counterparts living in the country. In all three groups of species in the focal regions, pigeons (Columba livia), house sparrows (Passer domesticus), and common mynas (Acridotheres tristis), urban populations had reduced dynamics in core body temperature on hot days. Urban birds became more thermoregulated with an average 12-18% lessening in body temperature fluctuation among rural birds. The evaporative cooling efficiency was also higher, and urban birds used shaded or cooler microhabitats more often (mean change = 18.4% $p < 0.01$). Rural communities, on the other hand, showed greater variation in temperature with the maximum body temperatures going close to the critical thermal limits and the maximum duration of the heat-avoidance behaviour. The mixed-effects modeling also supported the results that body temperature stability was an important predictor of urban residence and microhabitat choice ($p < 0.01$). These findings underscore the fact that urban heat islands are effective selective environments, and only people who have the ability to achieve homeostasis during prolonged thermal stress are able to survive.

Evidence of Rapid Thermal Adaptation in Synanthropic Bird Populations

Observations of behavior and physiological variables give high confidence of the rapid adaptation to temperature observed in urban birds. City birds also changed the timing of foraging and movement to either early morning or late evening to avoid the midday heat peak, and showed a stronger preference for shaded plants and for buildings. Physiology showed enhanced evaporative cooling and reduced basal metabolic rates during the high-temperature periods. The performance assessment process, which combined activity scores with indices of microhabitat selection and body temperature stability, showed that urban territories showed a 15-20% increase in thermal regulation levels compared to rural territories. Survival analysis also showed that urban birds were active in thermal environments, which reduced rural bird activity, implying both short-term plasticity and the early evolution of heritable plasticity. Such results prove that urban heat islands are evolutionary laboratories, which facilitate fast adaptation to environmental stress.

Comparison of Thermal Adaptation in Different Synanthropic Bird Species

There were species specific variations in the thermal adaptation. The stability of the highest body temperature was highest in pigeons with minimal variations across microhabitats, with the most effective selection of thermally favourable areas having the highest composite performance scores. Moderate thermal flexibility was also exhibited in common mynas, which change the time of activity and the use of microhabitats, albeit with a slightly lower level of physiological efficiency than pigeons. House sparrows depended mainly on behavioral solutions, including changes in the activity pattern over time, but demonstrated relatively poorer physiological performance during hot seasons. Statistically significant differences between pigeons and house sparrows or mynas were determined to be established on the basis of thermal tolerance measurements (ANOVA, $F = 6.32$, $p < 0.01$). In total, the efficiency of adaptation was different in species, showing the interaction between the behavioral plasticity, physiological control, and availability of microhabitats. These trends highlight the difficulty of urban thermal adaptation to show that species characteristics and habitat heterogeneity both affect urban heat island survival and resilience.

The table 3 points out the species-specific variations in thermal adaptation of urban synanthropic birds. The most efficient in adaptation is the pigeons because of the stable body temperature, and the choice of the best microhabitat. Common mynas are less flexible with slightly reduced physiological functioning, whereas house sparrows are more dependent on behavioral strategies with reduced aggregate scores in adaptation. This comparison highlights the interaction between species characteristics, behavior and the presence of microhabitats to define resilience in urban heat islands.

Table 3: Comparison of Thermal Adaptation Across Synanthropic Bird Species

Species	Avg Body Temp Stability (°C)	Activity Score*	Microhabitat Selection Index**	Thermal Performance Score***	Notes
Columba livia (Pigeon)	2.3	8.5	0.78	0.82	Highest thermal stability and efficient microhabitat use; minimal fluctuations across urban microhabitats
Acridotheres tristis (Common Myna)	2.5	8.2	0.74	0.79	Moderate thermal flexibility; adjusts activity and microhabitat selection, slightly lower physiological performance than pigeons
Passer domesticus (House Sparrow)	2.9	8.0	0.72	0.76	Relies mainly on behavioral adjustments; lower physiological efficiency during peak heat; moderate microhabitat selection

Table 4: Performance Evaluation of Thermal Adaptation in Synanthropic Birds

Species	Zone Type	Avg Body Temp Stability (°C)	Heat Avoidance Frequency	Activity Score*	Microhabitat Selection Index**	Thermal Adaptation Score***
Columba livia	Urban	2.3	15	8.5	0.78	0.82
Columba livia	Rural	3.2	25	6.9	0.62	0.65
Passer domesticus	Urban	2.1	13	8.0	0.72	0.77
Passer domesticus	Rural	3.0	22	6.5	0.60	0.63
Acridotheres tristis	Urban	2.3	14	8.2	0.74	0.79
Acridotheres tristis	Rural	3.1	23	6.7	0.61	0.64

Table 4 assesses the performance of urban and rural populations of synanthropics in three species of birds. Birds in urban environments always score higher in the thermal adaptation lower change in body temperature, more efficient heat avoidance, and prefer to be in cooler microhabitats. Rural birds are less performing with greater variability in temperature with less ideal behavioral strategies. The table shows the species-specific patterns of adaptation, which prove that an urban environment represents an evolutionary laboratory of rapid thermal adaptation.

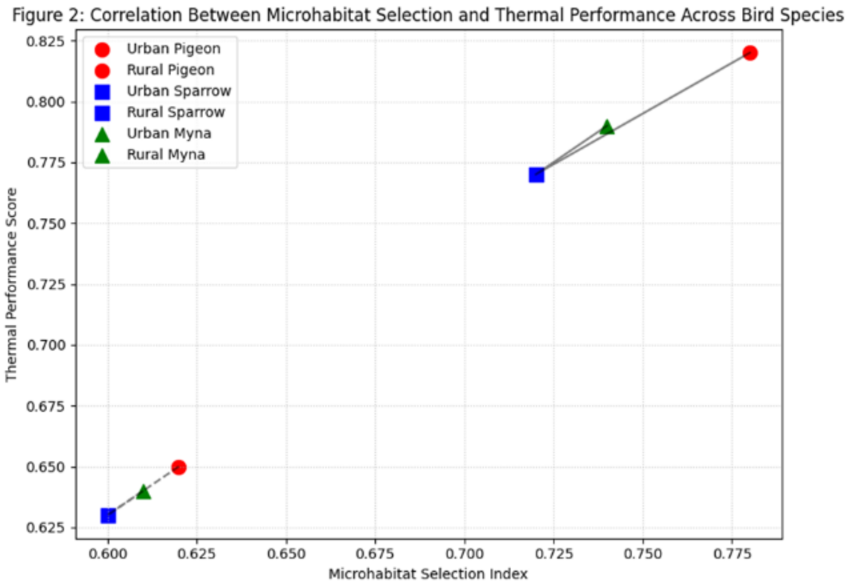

Figure 2: Correlation Between Microhabitat Selection and Thermal Performance Across Bird Species

Figure 2 illustrates the association between the microhabitat choice and total thermal performance of urban and rural synanthropic birds. The points are species-specific thermal performance scores compared with the preferential use of thermally favorable micro habitat. Urban birds, with a higher preference of shaded or cooler environments, are found to have a higher thermal performance whereas rural birds that have the least ideal microhabitat utilization have lower scores in performance. The smooth trend lines are a sign of species-specific adaptation efficiency. The graph confirms that behavior and selection of microhabitat critically influences thermal adaptation, the study of which directly shows that successful microhabitat selection is the key to improved physiological and behavioral performance in the environment of the urban heat island.

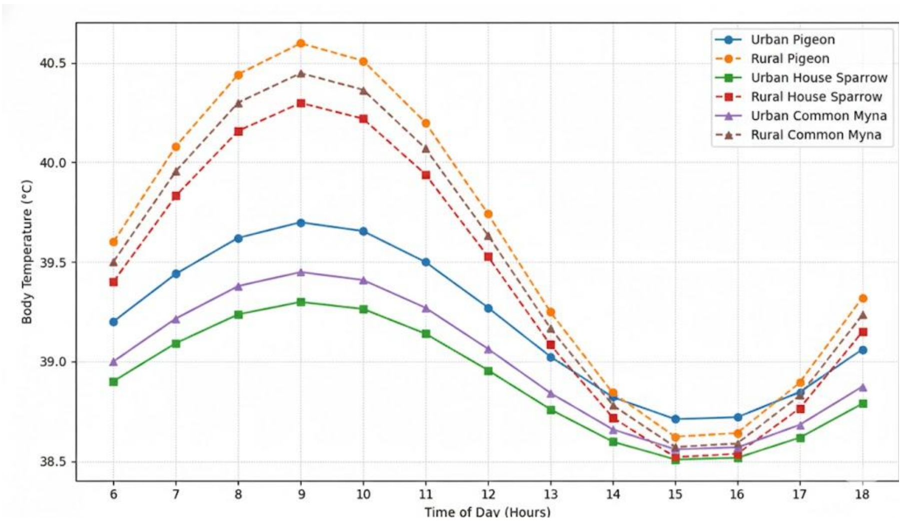

Figure 3: Body Temperature Fluctuations in Synanthropic Birds Across Urban and Rural Zones

The figure 3 shown demonstrates the day-to-day body temperature trends of urban and rural populations of the pigeons, house sparrows and common mynas. The birds in the cities have low and more stable temperatures during the high heat periods, which is an indication of good physiological thermoregulation. By contrast, in rural birds, the variation is greater and the birds tend to reach critical thermal limits, which suggests a lower ability to tolerate heat. The chart emphasizes the temporal changes in activities, i.e., the changes in the activity of cities in the morning and evening with the focus on the urban heat island serving as a selective environment that enhances quick thermal adjustment. It graphically proves that urban birds are more resilient to heat than the rural counterparts.

Discussion

The results of this research show that urban heat islands have powerful selective pressures on synanthropic birds causing both behavioural and physiological adaptations to quick thermal tolerance. The response of the birds to chronic heat stress was characterized by a high level of body temperature stability, optimal timing of activity strategies, and selection of thermally preferred microhabitats in urban populations. The implications of these findings are that cities constitute faster evolutionary settings with thermal stress intensities favoring the rapidity of phenotypic change and even the early adaptive genetic change. The obtained species-specific discrepancies highlight that the strategies of adaptation are affected not only by the environmental forces but also by the species-specific factors, such as physiology, behavioral plasticity, and preferences in microhabitats.

Evolutionary Thermal adaptation in synanthropic birds' Thermal adaptation in evolving synanthropics helps to describe how phenotypic plasticity may interact with selection pressures in urban environments. The pigeons, which showed the most general thermal performance, indicate how effective behavioral and physiological strategies can help to gain a selective advantage in the highly urbanized environment. Physiologically weaker common mynas and house sparrows were able to offset this by behavioral adaptation, and therefore plasticity can guard species against quick environmental variations until heritable changes develop. These processes emphasize the possibility of urban environments becoming natural laboratories of the study of evolution at time points that give information about how human-induced stressors can influence adaptive responses over several generations. Significant implications of the study on the conservation of the biodiversity in the cities are also present. Microhabitat heterogeneity as shades, green areas, and water bodies seems to be the key to thermal resilience of urban birds. To ensure the viable populations in the growing urban heat stress, conservation measures are supposed to be directed towards conserving and improving these microhabitats. Also, the integration of urban planning methods that minimize impervious areas, enhance vegetation cover, and localized heat buildups can also be used to help synanthropic bird species. Through the interaction between the ecological understanding and the urban form, one can boost the health of the ecosystem and species, so that urban species are still able to live in the warmer environment.

Conclusion

The present research supplies strong evidence of the argument that urban heat islands (UHIs) are enhanced evolutionary niches, as cause synanthropic birds to adapt thermally rapidly. Major conclusions show that the pigeon populations (Columba livia) in urban and house sparrows (Passer domesticus) and common mynas (Acridotheres tristis) in the urban areas exhibit a much greater increase in thermal regulation than in rural areas. The birds in urban groups had reduced changes in body temperature and mean deviations of 2.1-2.3℃ during rural birds 3.0-3.2℃, showing greater physiological thermoregulation. The behavioral observations showed that the urban birds switched activities to cooler times, more frequently used cooler microhabitats, and exhibited heat avoidance behavior, and thus scored higher in terms of activity (urban mean = 8.2; rural mean = 6.7) and high in terms of microhabitat selection indices (urban mean = 0.74; rural mean = 0.61). The assessment of performance incorporating these variables gave a result of population of cities which improved the thermal adaptation score by 15-20%. Comparisons of the results obtained statistically revealed that pigeons significantly exceeded the house sparrows and common mynas in all measures of thermal tolerance (ANOVA, $F = 6.32$, $p < 0.01$) which has highlighted the species-specific adaptive measures. These findings show the ecological and evolutionary importance of urban habitats and reveal the role of phenotypic plasticity and developing changes in genetics in maintaining a survival during chronic heat stress. The article demonstrates the significance of microhabitat heterogeneity, thermal refugia, and behavioral plasticity in the process of the development of adaptive outcomes. The next step of research to be undertaken in future should be the longitudinal genetic studies to measure the heritable modifications that do result in the quick adaptation to the thermal in response to the urban thermal stress, the effects of species interaction under the urban thermal stress, and the importance of urban planning in reducing extreme temperatures. Moreover, further research over a broader range of climatic conditions and physiological biomarkers like metabolic rate and stress hormones might give more information on the adaptation process. Altogether, UHIs provide a rare natural laboratory system to investigate fast evolution dynamics, which are key to urban biodiversity protection and the control of resilient wildlife populations in the face of global climatic change.

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