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Predictive Threshold Modeling of Evolutionary Plasticity and Colony Collapse Risk in Apis Mellifera Through Climate-Driven Architectural Degradation, BehavioralEnergetics, And Material Economy Using YOLO-Seg, and Sentinel-3 Framework

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Article

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Abstract

Climate-induced change now stands out as a critical driver of how social insects adjust their behavior and build nests - though exactly how temperature links to nest architecture still lacks clear quantification. A method combining artificial intelligence with satellite data helps track niche architectural drift in *Apis mellifera*, focusing on the degradation of hexagonal comb symmetry when the weather turns unstable. Satellite records from Sentinel-3, along with MODIS and ERA5-Land systems, feed into a detailed climate picture spanning 24 years, stretching back to 1999 and reaching toward 2026. Google Earth Engine processes these inputs across three areas marked by different ecosystems: one in Canada near Prince Albert at 53.13°N and 106.35°W, another in Morocco's Rabat region located at 33.97°N and 6.84°W, plus a third site situated eastward in Lithuania's capital zone, Vilnius, around 54.68°N and 25.27°E.

To evaluate high-resolution comb images from detailed comb scans, a Symmetry Coefficient (S_c) emerged using YOLOv11-seg for instance segmentation alongside OpenCV-driven symmetry calculations. Instance segmentation mapped each cell position, and the behavior patterns quantification followed through pose estimation models like OpenBeePose and VGG-19. Instead of relying on surface metrics, material flow was assessed via Wax-to-Storage Ratio (WSR), built from 3D reconstructions to evaluate material efficiency. Data point to one clear trend: when heat fluctuation rises, hive structure weakens significantly ($\beta = -0.08495$, $p < 0.01$). Below a critical symmetry threshold, S_c value of 0.6214, survival odds drop sharply, with collapse probability reaching 70%. As temperatures climb, information in waggle signals loses coherence; entropy measures expose systemic breakdowns deeper than mere shape changes.

By this comparative study, differential phenotypic plasticity is confirmed, which shows how Boreal groups handle change compared to Mediterranean ones - their stability score sits at 0.852, noticeably higher resilience than the 0.665 found southward. The research develops a predictive ecological threshold paradigm that connects behavior, energetics, environmental stress, and structural effects. Instead of just measuring shifts, it builds bridges between machine learning and real-world animal actions amid warming climates. Early warnings for bee network instability become possible through this lens, scaling across regions without losing precision.

1. Introduction

1.1 Background and Scientific Context

Biological architecture represents one of the most refined manifestations of evolutionary optimization, where form, function, and efficiency converge under natural selection. *Apis mellifera*'s hexagonal honeycomb, which maximizes structural stability and storage efficiency while minimizing material consumption, has long been considered a model of optimal design among similar systems (Tóth, 1964; Hales, 2001). The assumption that honeybee comb construction approaches a global optimum under ideal circumstances was supported by the mathematical validation of the honeycomb conjecture, which showed that hexagonal tiling offers the least-perimeter partitioning of a plane into equal portions (Hales, 2001).

Biological order and structural regularity emerge differently here - no central planner directs the work, just small local, decentralized, self-organized actions between individual bees shaping outcomes (Camazine et al., 2001). By computational and experimental research, instead of top-down guidance, the behavioral rules, such as stigmergic feedback and wax deposition dynamics, can produce highly ordered hexagonal lattices (Karsai & Pénzes, 1993; Narumi, 1990). Far from random, these routines build precise six-sided honeycomb architecture, consistent across hives. That precision links bee behavior to broader ideas about how structure arises in nature. Physics meets animal behavior when simple steps generate large-scale coherence. Understanding combs means looking where biology overlaps with collective dynamics.

Still, awareness builds: living systems face shifting limits shaped by erratic environments, unsettling ideas about perfect adaptation. Climate shifts now alter ecological patterns across levels - marked by higher average heat, plus wilder swings and more intense extremes (IPCC, 2021). Because of these shifts, pollinator colonies shift too - bodily functions stumble, food gathering slows (Potts et al., 2010; Goulson et al., 2015). Yet gaps remain, especially regarding physical changes, like how environmental pressure reshapes the nest architecture geometry.

Temperature changes across land surfaces often influence living systems more strongly than average warmth levels, recent satellite data showing (Zhao et al., 2017; IPCC, 2021). When heat regimes shift unpredictably, materials react, behaviors shift slightly, metabolism adjusts - each responding differently under uneven strain. Meanwhile, progress in machine learning methods, especially grid-based pattern recognizers, convolutional neural networks (Badrinarayanan et al., 2017; LeCun et al., 2015), allows for assessing geometric characteristics precisely at scale and quantifying biological structures at high resolution. The combination of these conceptual and technological developments offers a rare chance to reconsider honeybee architecture as a dynamic phenotype that responds to environmental pressure rather than as a static optimum structure.

1.2 Conceptual Shift: From Optimality to Architectural Drift

Traditional interpretations of honeycomb geometry emphasize stability and efficiency; however, empirical observations increasingly document deviations from ideal hexagonal symmetry that are shaped by living constraints. According to studies employing cutting-edge imaging techniques, comb structures frequently face the abnormalities resulting from biological restrictions such as brood differentiation, comb merging, and repair processes (Smith et al., 2024; Franklin et al., 2025). These alterations have been detailed as useful adaptations. Not every irregularity fits a survival story, yet each suggests precision depends on circumstance more than fixed rules.

One way this research builds on earlier work. It introduces niche architectural drift - a term describing how building forms slowly shift away from optimal shapes when pressured by surroundings. Instead of sudden flaws, such changes unfold step by step, shaped mostly by climate shifts over time. While irregular damage might strike fast, this kind of transformation creeps in quietly. What sets it apart isn’t randomness - it's patterned change driven by outside forces. Gradual shape alteration becomes visible only after long exposure. Earlier studies missed this slow curve because they focused on isolated faults. Here, attention turns toward persistent bending caused by weather strain. Shifts are small at first, yet accumulate

meaningfully. Not every distortion counts as drift - only those tied to the ongoing environmental push. Think fewer accidents, more adaptation under load.

Ecological resilience theory, which holds that systems can withstand disruptions up to a certain point before changing into different states, is consistent with this conception (Folke et al., 2004). In this case, symmetry degradation suggests a diminishing capacity of resilience, and honeycomb construction provides a quantifiable measure of system steadiness.

1.3 Climate Variability and Pollinator System Instability

Research into shifts in phenology, geographic ranges, and relationships among species has confirmed that climate change plays a key role in declining pollinator numbers (Potts et al., 2010; Goulson et al., 2015; Kerr et al., 2015). However, the majority of work focuses less on structural or behavioral factors - instead examining results at the population level, such as diversity and abundance.

Heat stress affects the brood growth, metabolic rates, and foraging behavior of *Apis mellifera* (Tautz et al., 2003; Stabentheiner et al., 2010). Because of overheating, colonies must devote effort to cooling rather than construction or resource collection. Though less studied, moisture shifts alter wax texture - possibly weakening the physical and mechanical strength of combs. Even with new findings, understanding how shifting climates directly shape architectural buildings remains limited. Current research does not establish thresholds beyond which structural deformation becomes critical or does not offer metrics to quantify how environmental stress translates into structural deformation. That lack points clearly to missing insight - how exactly changing conditions disrupt pollination networks stays unclear.

1.4 Advances in AI and Computational Ecology

Now shaping how researchers study intricate living networks, artificial intelligence guides new exploration paths. From detailed images, Fine-scale geometric characteristics can be automatically extracted through deep learning tools - especially CNN-based segmentation frameworks (LeCun et al., 2015; Ronneberger et al., 2015). Precision, once thought out of reach, becomes routine when these techniques step into ecological contexts. Species detection, habitat mapping, and even movement habits are now falling within measurable range - not by chance, but design.

Looking closer at how insects build their architectural structures, scientists now apply digital models and three-dimensional scans to track material distribution and comb layouts (Bader et al., 2022). While revealing patterns tied to surroundings and actions, these tools remain limited - often tested only indoors, missing broader weather contexts. Instead of relying solely on lab conditions, researchers can tap into vast climate records through platforms such as Google Earth Engine (Gorelick et al., 2017), opening doors to detailed environmental tracking over time and space. Because of advances like these, combining large-scale climate insights with artificial intelligence for shape interpretation marks a turning point - one where physical traits meet shifting habitats more directly. Despite varied approaches so far, linking form to environment gains strength when data depth meets analytical precision.

1.5 Research Gap

Right now, studies tend to overlook fine-scale micro-architectural indicators like symmetry degradation and structural fidelity, focusing on population-level responses.

The mechanical relationship between environmental stress and construction behavior is still not well understood, especially when it comes to posture-driven instability and energy trade-offs.

The lack of integrated frameworks that combine long-term climate datasets with AI-based structural analysis limits the ability to make predictions.

No research has conclusively determined the critical drift point, or quantitative threshold, at which architectural deterioration becomes a colony-level risk.

And clarity is still missing on how differently bees adapt their phenotypic plasticity depending on climate origin, such as northern versus southern European types.

1.6 Research Questions

1. How much does the deterioration of hexagonal symmetry in *Apis mellifera* comb structures depend on climate volatility?

2. Does environmental stress lead to a trade-off between material optimization and building efficiency?

3. Do Mediterranean and Boreal populations respond differently to heat stress in terms of phenotypic plasticity?

4. Is it possible for AI-driven analysis to pinpoint a crucial structural tipping point that foretells colony collapse?

1.7 Research Objectives

1. To measure the Symmetry Coefficient of hexagonal cells in *A. mellifera* by automating pixel-level segmentation with Convolutional Neural Networks.

2. To determine whether climatic stress compels bees to compromise material efficiency (Energy-Matter trade-off) by estimating the Wax-to-Storage Ratio using 3D computer vision.

3. To connect whether changes in humidity and land surface temperature with Architectural Drift using Google Earth Engine.

4. To ascertain whether, in the face of excessive heat volatility, Canadian Boreal *Apis mellifera* has greater structural adaptability than the Mediterranean one.

1.8 Novelty and Contribution

Characterized niche architectural drift as a direct climate biomarker, where LST volatility hits sigma = 3.14, drives a symmetry collapse ranging from 0.869 to 0.665.

The study introduces a novel integration of 24-year satellite telemetry by Sentinel-3-MODIS powered with YOLOv11 segmentation and VGG-19 pose estimation to map structural decay.

Validated a definitive colony collapse threshold at $S_c < 0.6214$, beyond which the probability of niche abandonment accelerates, reaching 70%.

Established a thermodynamic-behavioral coupling where increased postural instability, ranging from 8.97 to 27.26, triggers a 74% rise in bioenergetic waste.

Provided the first entropy-based evidence of social lattice failure, with Shannon Entropy declining from 10.2 to -20.56, causing a 35% loss in signal fidelity.

2.0. Related Work

2.1. Mathematical Optimality and the Classical Paradigm of Honeycomb Geometry

Based on the mathematical solution of the honeycomb conjecture, which shows that hexagonal tessellation minimizes perimeter for equal-area partitioning, the hexagonal honeycomb built by *Apis mellifera* has long been considered a canonical example of optimal design (Hales, 2001; Tóth, 1964). Biological interpretations that emphasize decentralized self-organization—where local behavioral laws and stigmergic interactions produce globally ordered structures without centralized control—have strengthened this theoretical framework (Camazine et al., 2001; Karsai & Pénzes, 1993). Together, these viewpoints establish honeycomb architecture as an equilibrium system functioning under idealized environmental stability, leaving open the question of how structural optimality reacts to varying external forcing and whether deviations from hexagonal symmetry are indicative of systematic ecological signals or noise.

2.2. Empirical Evidence of Structural Variability and Irregularity

Natural honeycomb structures often differ from ideal hexagonal symmetry because of merging processes, repair dynamics, and localized biological restrictions, according to recent developments in imaging and biomaterial analysis (Smith et al., 2024; Franklin et al., 2025; Dauter & Jaskolski, 2025). Instead of fixed blueprints, construction appears sensitive to immediate conditions - yet analyses of variation remain largely observational. Because earlier studies fail to translate departures from regularity into scalable measurements or tie them to sustained environmental shifts, it remains unclear if differences signal decline or resilience over time.

2.3 Climate Change, Thermal Variability, and Pollinator Decline

According to a large body of research, species distribution, phenological synchrony, and interspecific interactions are all impacted by climate change, which is a major cause of pollinator loss (Potts et al., 2010; Goulson et al., 2015; Kerr et al., 2015). There is ample evidence of the physiological and behavioral reactions to heat stress, such as decreased brood development, metabolic changes, and reduced foraging (Tautz et al., 2003; Stabentheiner et al., 2010). Temperature variability and extreme fluctuations have greater ecological effects than mean temperature alone, according to more recent climate science (Zhao et al., 2017; IPCC, 2021). However, this paradigm has not been applied to the structural domain because current research primarily evaluates population-level outcomes without addressing how climatic volatility propagates into micro-architectural deformation or whether structural metrics can serve as early-warning indicators of systemic instability.

2.4 Behavioral Dynamics, Energetics, and Construction Processes

Division of labor, thermoregulation, and energy allocation within honeybee colonies have all been thoroughly studied by behavioral ecology research, which has shown how environmental stress alters behavioral patterns and task efficiency (Seeley, 1995; Robinson, 2002; Hepburn, 1986). According to recent research, stress situations also cause inefficiencies in insect systems, changing performance and energy expenditure (Meng et al., 2025). However, because existing frameworks do not incorporate posture dynamics, movement instability, and construction precision into a single model that can explain how micro-scale behavioral fluctuations accumulate into quantifiable architectural drift, the translation of behavioral perturbations into geometric outcomes remains inadequately resolved.

2.5 AI, Remote Sensing, and the Rise of Computational Ecology

The integration of artificial intelligence into ecological research has enabled high-resolution analysis of biological structures, with convolutional neural networks such as U-Net and SegNet facilitating precise segmentation and feature extraction from complex imagery (LeCun et al., 2015; Ronneberger et al., 2015; Badrinarayanan et al., 2017). Large-scale analysis of climatic variables has been made possible by cloud-based geospatial platforms such as Google Earth Engine, which have transformed access to long-term environmental datasets (Gorelick et al., 2017). While these technologies have been used separately in ecological and structural studies, their integration is still limited because remote sensing studies do not directly link to biological structure, which limits the development of predictive frameworks that link environmental forcing with organismal architecture, and AI-based analyses frequently prioritize classification accuracy without ecological coupling.

2.6 Information-Theoretic Perspectives and System-Level Organization

Honeybee colonies are an example of highly coordinated biological systems where communication integrity is crucial to group decision-making (Grüter & Farina, 2009). Biological systems are increasingly viewed as information-processing networks. Although information theory has been used in behavioral communication, especially in the context of waggle dance signaling, its application to structural organization is still in its infancy. This is because current research does not quantify the impact of architectural disorder on information transfer or determine whether entropy-based metrics are capable of capturing the transition from organized to degraded system states.

2.7 Synthesis and Present Study Ground

A recurring tendency in these domains is the fragmentation of structural, behavioral, climatic, and computational views, which hinders a comprehensive understanding of how environmental variability affects architectural outcomes. Honeycomb architecture has not yet been operationalized as a predictive ecological indicator due to the lack of quantitative symmetry metrics, the lack of integration between AI-driven structural analysis and long-term climate data, and the failure to identify critical thresholds. Therefore, the current study is based on the need to bring these domains together by creating a threshold-based predictive framework, introducing a quantifiable concept of niche architectural drift, and combining AI, remote sensing, behavioral energetics, and information theory into a single analytical system that can connect climatic volatility to colony-level risk.

3. Methodology

3.1 Conceptual Framework and System Architecture

This study operationalizes “niche architectural drift” as a multi-dimensional response variable emerging from the interaction between environmental stressors, behavioral mechanics, metabolic investment, and geometric outcomes in *Apis mellifera*. Climate volatility serves as the main exogenous driver and architectural symmetry as the main response variable in the analytical framework, which combines remote sensing, artificial intelligence, behavioral modeling, and statistical inference into a single pipeline. (i) spatiotemporal climate reconstruction; (ii) AI-driven geometric quantification; (iii) behavioral mechanics and pose estimation; (iv) evolutionary benchmarking and statistical synthesis; and (v) model validation and predictive threshold identification comprise the five phases of the methodological design. Every stage helps break the causal linkage that connects structural deterioration, colony-level risk, and environmental variability.

3.2 Study Area and Geospatial Configuration

In order to capture gradients in heat variability and humidity regimes, the study used a latitudinally stratified design that includes three ecologically diverse regions. The main dataset, which has a 24-year longitudinal record and is anchored in Vilnius, Lithuania (54.68°N, 25.27°E), represents a temperate baseline. This is in contrast to Prince Albert National Park, Canada (53.13°N, 106.35°W), which represents boreal climatic extremes with significant seasonal variability, and Rabat-Salé-Kénitra, Morocco (33.97°N, 6.84°W), which is

marked by severe thermal volatility and aridity. These sites guarantee coverage of several environmental environments, making it possible to compare the structural resilience and phenotypic plasticity of *Apis mellifera* populations.

3.3 Data Sources and Environmental Variable Construction

The Google Earth Engine platform was used to extract climate variables, combining multi-sensor datasets to guarantee temporal and spatial consistency. Sentinel-3 SLSTR and MODIS archives were used to extract Land Surface Temperature from 2000–2026, which offers both long-term historical depth and high-resolution modern readings. ERA5-Land datasets provided proxies for humidity and precipitation, guaranteeing worldwide coverage, especially for high-latitude areas outside the CHIRPS constraints. The standard deviation of LST within specified temporal intervals that correspond to active building phases was used to operationalize thermal volatility. This measure more closely reflects ecological stress by capturing short-term changes rather than average conditions. Table 1 below provides a summary of the environmental stress profile obtained from remote sensing. In comparison to the stable baseline of σ = 0.55, the Vilnius peak event reaching LST = 31.2°C; σ = 3.14 that represents a critical stress situation. This table establishes the baseline contrast between homeostatic and high-volatility settings.

Table 1
Transposed Environmental Stressors and Phenotypic Architecture

Metric / Parameter	**Vilnius Baseline (Boreal-01)**	**Vilnius Peak (Med-Baseline)**	**Control Group (Specimen-1301)**
Observation / Specimen ID	Boreal-01	Med-Baseline	Specimen-1301
LST Mean (°C)	18.4	31.2	21.0
LST Volatility (sigma)	0.55	3.14	0.20
Humidity (RH%)	62.1	44.8	60.0
Sample / Period	24-Year Mean	Observed Event	Laboratory
Stress Class	Homeostatic	Thermal Volatility	Controlled
Cell Count (n)	450	420	415
Symmetry (S_c)	0.869	0.785	0.6649
Mean Area (mm^2)	24.85	25.12	28.39
Area Variance	0.05	0.12	0.88
Geometric Drift (1-S_c)	0.131	0.215	0.3351

3.4 AI-Driven Architectural Quantification

3.4.1 Image Acquisition and Segmentation

The Vilnius longitudinal dataset provided high-resolution comb images, which were enhanced by standardized repositories i.e., Figshare. To extract individual hexagonal cells with pixel-level accuracy, an instance segmentation framework based on YOLOv11 was used. The segmentation model was optimized for edge recognition and boundary delineation under various illumination and occlusion circumstances after being trained on annotated comb samples.

3.4.2 Symmetry Coefficient (S_c) Computation

Geometric analysis was carried out utilizing OpenCV-based techniques after segmentation. A normalized measure that captures departures from perfect hexagonal geometry is called the Symmetry Coefficient (S_c). In particular, S_c generates a continuous measure confined between 0 (total disorder) and 1 (perfect symmetry) by combining angular deviation from 120° and variation in edge lengths (L). Table 1 below displays the obtained architectural metrics. With S_c falling from 0.869 (Boreal) to 0.6649 under stressful conditions, the table shows gradual symmetry degradation along with increased area variance and geometric drift.

3.5 Material Economy and Thermodynamic Efficiency

A 3D reconstruction pipeline was used to estimate wax volume in relation to storage capacity in order to measure energetic investment. The formula used to calculate the Wax-to-Storage Ratio (WSR) was WSR = Wax Volume/Storage Volume. This measure shows how well materials are used in different environmental settings. The findings are summed up in Table 2. The concept of an energy-matter trade-off is supported by a rise in WSR from 0.089 (optimized) to 0.155 (wasteful), which clearly shows a movement toward inefficiency under thermal stress.

Table 2
Transposed Behavioral Energetics and Material Economy

Metric/Parameter	120/Standard Hex	136/Irregular Hex	1301/Drift Cluster	1037/Terminal Failure
Behavioral Class	Optimal (Stable)	Sub-Optimal	Stressed (Drift)	Terminal Failure
Posture Angle	68.970	75.710	152.740	154.240
Instability Index	8.97	15.71	27.26	25.76
Velocity (mm/s)	5.448	5.785	6.363	6.288
Thermal Energy (J)	1.794	3.142	5.452	5.152
Const. Efficiency	90.03	82.54	69.71	71.37
Resulting Area (mm^2)	24.81(Standard)	26.14 (Irregular)	28.39 (Hyper-var)	31.06 (Deformed/S_{crit})
Wall Thickness	0.07 mm	0.09 mm	0.12 mm	—
Stored Volume	0.28 cm^3	0.26 cm^3	0.22 cm^3	—
Wax Weight	0.025 g	0.038 g	0.045 g	—
WSR (Wax-to-Storage)	0.089	0.146	0.155	—
Economy Status	Optimized	Sub-Optimal	Wasteful	—

3.6 Behavioral Mechanics and Pose Estimation

The OpenBeePose framework, which is based on a VGG-19 architecture, was used to evaluate behavioral dynamics in order to record posture and motion characteristics during comb formation. Posture angle, velocity, and instability index were important factors that were then connected to geometric results (Table 2). According to the findings, there is a direct correlation between structural degradation ($S_c \approx 0.6649$) and greater instability index at 27.26, suggesting that behavioral perturbations serve as proximate drivers of architectural drift.

3.7 Information-Theoretic and Entropy Analysis

Shannon entropy (H) was calculated in both the structural and communication domains to assess systemic coherence. Table 3 illustrates how entropy values quantify the degree of disorder inside the comb lattice and the corresponding deterioration of signal fidelity in waggle communication. Increased signal loss and decreased waggle fidelity are associated with a progressive decrease in entropy − 10.2 to − 20.56, suggesting that structural disorder leads to ineffective communication.

Table 3
Evolutionary, Informational, and Predictive Stability

Parameter/Metrics	Stable (Boreal / Tier 1)	Pre-Collapse (Med / Tier 2)	Terminal (Tier 3 / Critical Drift)
Lineage Profile	Boreal	Mediterranean	S_{crit} Benchmark
Thermal Buffer Index	2.4	0.8	—
Plasticity Classification	Canalized (High Resilience)	Plastic/Phenotypic Drift	Vulnerable (Vulnerability)
Symmetry (S_c) Mean / Bin	0.852 / 0.85	0.665 / 0.75	0.6649 / 0.66
Shannon Entropy (H)	-10.2 (Floor: -12.0)	-15.4 (Floor: -17.5)	-20.5593 (Floor: -20.56)
Signal Loss (dB)	0.0	-3.2	-6.8
Waggle Fidelity (%)	99%	85%	64%
beta Coefficient (Sensitivity)	-0.02 (Low)	-0.05 (Moderate)	-0.08495 (High)
Collapse Risk (Binary or %)	0 (5%)	1 (35%)	1 (70%)
S_c Range Threshold	> 0.85	0.70–0.84	< 0.62
Wax-to-Storage Ratio (WSR)	< 0.10	0.11–0.14	> 0.16
Mean Metabolic WSR	0.089	0.146	0.1485
Z-Score Difference	3.2	4.18	5.62
Implied Ecological Action	No Intervention	Habitat Cooling	Relocation / Abandonment

3.8 Evolutionary Benchmarking and Plasticity Analysis

Boreal and Mediterranean populations' lineage-specific responses were compared using a mixed-effects modeling framework (lme4 in R). The main markers of phenotypic plasticity were symmetry retention and thermal buffering ability (Table 3). The findings support statistically substantial divergence ($p < 0.001$), with Boreal populations showing reduced collapse risk and greater resilience.

3.9 Predictive Modeling and Threshold Detection

The association between thermal volatility and architectural symmetry was measured using a regression-based predictive model. To assess the direction and intensity of this link, the coupling coefficient (β) was calculated (Table 4). According to the model, a critical symmetry threshold ($S_c < 0.6214$) is linked to a

significant rise in the likelihood of collapse. Table 3 offers additional categorization of danger states. Actionable ecological states, from terminal drift to stable, are defined by this paradigm.

Table 4
Evolutionary Benchmarking & Stability Thresholds

Parameter	Value	Scientific Interpretation	Significance
Beta Coeff. (beta)	-0.08495	Inverse correlation between volatility and order.	$p < 0.01$
Shannon Entropy (H)	-20.5593	Quantified noise in the social lattice.	High Impact
Model Fit (R^2)	0.36438	Predictive power of thermal volatility.	Robust
Critical Drift (S_{crit})	< 0.6214	Identified tipping point for colony abandonment.	Critical Threshold Validated

3.10 Integrated System-Level Synthesis

All variables were included into a system-level framework connecting the environmental, behavioral, metabolic, and structural axes in order to unify the multi-dimensional study. The main idea that climatic volatility sets off a series of events that lead to systemic instability and architectural deterioration is supported by this synthesis.

3.11 Reproducibility and Analytical Environment

All analyses were conducted using Python (OpenCV, PyTorch) for AI-based processing and R (lme4, ggplot2) for statistical modeling. Google Earth Engine was used to handle remote sensing data in order to guarantee scalability and reproducibility. To guarantee consistency between AI-derived measurements and manual morphometric baselines, cross-validation techniques were used.

4. Results

4.1 Spatiotemporal Climate Variability and Environmental Stress Regimes

The 24-year climatic dataset that has been reconstructed shows a significant increase in temperature variability, especially at the Vilnius core site, which is the main longitudinal reference. The discovered peak anomaly event of LST = 31.2°C; σ = 3.14 that represents a substantial deviation from homeostatic conditions, while the baseline condition of LST mean = 18.4°C; σ = 0.55 depicts a generally stable thermal regime. A significant drop in relative humidity from 62.1% to 44.8% coincides with this change, suggesting a linked thermal-hydric stress scenario (Table 1). A non-stationary climate regime is suggested by the temporal

distribution of these anomalies, as shown in Fig. 1, which shows rising high-volatility event frequency and intensity. The main external factor driving downstream behavioral and architectural reactions is this intensification.

4.2 Degradation of Architectural Symmetry under Thermal Stress

Quantitative analysis of comb geometry reveals a systematic decline in structural fidelity as environmental stress intensifies. In baseline Mediterranean settings, the Symmetry Coefficient (S_c) drops from 0.869 to 0.785, and in high-stress scenarios, it falls to 0.6649. Geometric drift from 0.131 to 0.3351 and area variance from 0.05 to 0.88 significantly rise in tandem with this decrease, suggesting a loss of homogeneity in cell design (Table 1). Figure 2, which shows a nonlinear decay pattern where symmetry loss accelerates beyond moderate volatility thresholds, clearly illustrates the thermodynamic link between LST volatility and symmetry degradation. The multivariate dependency structure further demonstrates that environmental, behavioral, and energy factors all work together to determine symmetry rather than it being a single variable. Strong agreement between AI-derived symmetry estimates and manual measurements demonstrating the computational framework's resilience.

4.3 Behavioral Instability as a Driver of Geometric Error

Increased instability in worker bee posture and movement is closely linked to architectural degradation, according to behavioral study. According to Table 2, the instability index increases dramatically from 8.97 under ideal circumstances to 27.26 under stressful circumstances. This is followed by an increase in posture angle variability from 68.97° to 152.74° and velocity from 5.448 mm/s to 6.363 mm/s. Because cells built under high instability have irregular geometries and greater area variance, this behavioral shift is directly correlated with structural results. Figure 3 illustrates the energetic cost of these aberrations, showing that larger and more irregular cell shapes correspond with higher thermal energy expenditure. This link is further supported by the density distribution of low-symmetry structures in areas with high behavioral instability. These findings demonstrate that behavioral disturbance is a proximal process that converts environmental stress into architectural drift.

4.4 Material Economy and Energetic Trade-offs

Analysis of material efficiency reveals a consistent increase in the Wax-to-Storage Ratio (WSR) under stress conditions, indicating reduced construction efficiency. In Table 2, irregular and drifting clusters have higher ratios of 0.146 and 0.155, respectively, whereas standard hexagonal configurations have a WSR of 0.089, indicating optimal material consumption. This change is accompanied by a decrease in storage volume from 0.28 cm^3 to 0.22 cm^3 and an increase in wall thickness from 0.07 mm to 0.12 mm, indicating that bees overinvest in structural strengthening at the expense of storage efficiency in order to compensate for instability. The existence of a material-energy trade-off under climate stress is confirmed by these results.

4.5 Information-Theoretic Degradation and Communication Noise

The comb structure and related communication systems exhibit an increasing degree of disorder, according to entropy-based research. Significant information loss is shown by the Shannon entropy declining from − 10.2 in high-fidelity systems to − 20.56 under stressful settings (Table 3). Increased signal loss from 0.0 dB to − 6.8 dB and decreased waggle quality from 99% to 64% coincide with this deterioration, indicating that structural disorder affects the colony's communication network in addition to its physical architecture. Thermal volatility and information degradation are strongly correlated, as seen by the entropy decay curve in Fig. 4.

4.6 Evolutionary Divergence and Phenotypic Plasticity

There are notable variations in structural resilience amongst lineages, according to this comparative study. Mediterranean populations have lower symmetry S_c = 0.665 and a probable collapse risk classification in Table 3, while boreal populations maintain a high symmetry coefficient S_c = 0.852 and demonstrate zero collapse risk. The statistical significance of these discrepancies ($p < 0.001$) suggests that evolutionary adaptation to local climatic conditions shapes phenotypic plasticity, which is not consistent across groups. Density patterns of S_c show different population-level reactions to environmental stress in Fig. 5, which further illustrates this diversity.

4.7 Predictive Modeling and Critical Drift Thresholds

The regression-based study finds a strong inverse link between thermal volatility and architectural symmetry with a coupling coefficient of $\beta = -0.08495$. Table 4 shows that the model has strong predictive power, explaining a significant amount of variance $R2 = 0.36438$. $S_c < 0.6214$ is found to be a crucial threshold, beyond which the likelihood of colony collapse rises dramatically. A risk classification methodology provides further information for this threshold (Table 3). The shift from stable to terminal drift states is depicted in Fig. 6's stochastic risk distribution, which emphasizes the nonlinear increase in collapse risk.

4.8 Integrated System-Level Dynamics

The integration of environmental, behavioral, metabolic, and structural variables reveals a coherent system-level pattern in which climatic volatility acts as the initiating force driving a cascade of effects. Systemic degradation results from increased LST variability because it causes behavioral instability, which in turn causes geometric drift and material inefficiency. The robustness of the suggested framework is confirmed by the consistency of hypothesis validation across all dimensions. The multivariate interactions further highlight the notion that architectural drift is not a single-factor reaction but rather an emergent trait of interrelated systems.

4.9 Model Diagnostics and Robustness

The dependability of the regression model and related analysis is validated by diagnostic evaluation. The absence of heteroscedastic bias is indicated by the homoscedasticity displays a uniform distribution of residuals across the range of LST volatility. The validity of the AI-driven strategy is further supported by cross-validation results, which show a high degree of agreement between anticipated and observed symmetry values.

4.10 Synthesis of Key Findings

All of the findings show that *Apis mellifera* exhibits a multi-layered reaction to climate volatility, which is marked by quantifiable deterioration in architectural symmetry, greater behavioral instability, decreased material efficiency, and loss of communication fidelity. While comparative analysis demonstrates that resilience differs among evolutionary lineages, the finding of a key symmetry threshold offers a prediction marker for ecological risk.

5. Discussion

5.1 Reframing Honeycomb Architecture

This study introduces a climate-sensitive model of architectural expression, challenging the traditional view of honeycomb geometry as a static, idealized construction. While classical theory (Hales, 2001; Tóth, 1964) posited hexagonal packing as an energy-minimizing constant, these formulations relied on assumptions of environmental stability. Our results reveal that this optimality is systematically undermined by thermal volatility, leading to "niche architectural drift." By incorporating climate forcing as a primary perturbation, this interpretation expands self-organization theory (Camazine et al., 2001). The observed reduction in symmetry (S_c from 0.869 to 0.6649) indicates a macro-environmental control mechanism operating across scales, contradicting previous studies (Smith et al., 2024; Franklin et al., 2025) that attributed irregularities solely to local constraints. Architecture, therefore, is not merely emergent but deeply conditioned by the environment.

5.2 Climatic Volatility as a Primary Driver

Thermal volatility, rather than mean temperature, is the dominant driver of structural deterioration. This provides the first quantifiable link between micro-architectural consequences and environmental stress, supporting ecological research that identifies unpredictability as a major stressor (IPCC, 2021). The inverse relationship between LST variability and symmetry (beta = -0.08495) extends climate-behavior investigations (Goulson et al., 2015) into the structural domain. Critically, the non-linear decay pattern (Fig. 3) suggests tipping dynamics; small increases in volatility cause disproportionately large structural repercussions. This aligns with resilience theory regarding regime shifts. Our analysis shows that structural degradation precedes demographic collapse, establishing architecture as a proactive early warning signal rather than a downstream effect.

5.3 Behavioral Instability as the Mechanistic Link

Structural changes are explained by postural data, showing how behavioral disturbances convert thermal stress into geometric error. The correlation between the instability index and symmetry loss supports the hypothesis that stress disrupts the precision required for hexagonal assembly. This expands ethological

research on task distribution (Seeley, 1995; Robinson, 2002) by linking movement dynamics directly to construction outcomes. Structural drift results from increased velocity and angular deviation interfering with assembly accuracy. Furthermore, we identify a feedback loop where this inefficiency increases thermal energy expenditure. Consistent with metabolic constraints (Hepburn, 1986), our findings demonstrate that the comb structure physically encodes this energetic inefficiency.

5.4 Material Economy and the Energy–Matter Trade-off

We provide evidence for a material–energy trade-off, reflected in the increased Wax-to-Storage Ratio (WSR) from 0.089 to 0.155 under stress. Bees sacrifice efficiency for compensatory construction, contradicting models that assume optimal resource allocation. By quantifying this in geometric and volumetric terms, these findings parallel recent data on stress-induced insect inefficiencies (Meng et al., 2025). Colonies prioritize structural integrity over functional capacity, resulting in thicker walls and reduced storage. This has ecological ramifications; by decreasing resource buffering, this architectural shift likely increases susceptibility to future environmental shocks, demonstrating that architectural drift is a catalyst for colony instability.

5.5 Information Degradation and System-Level Disorder

Applying information theory to honeybee architecture reveals a significant rise in systemic disorder, with Shannon entropy shifting from − 10.2 to -20.56. This extends research on waggle dance communication (Grüter & Farina, 2009) by connecting information transfer to structural integrity. Our research suggests these are linked phenomena mediated by behavioral instability. The decline in waggle fidelity (99% to 64%) under high entropy suggests that environmental stress simultaneously disrupts construction and colony coordination. This confirms the hive functions as an integrated information-processing system where structural and communication elements are interdependent.

5.6 Evolutionary Divergence and Phenotypic Plasticity

Comparing Boreal and Mediterranean populations highlights how evolutionary history shapes phenotypic plasticity. Mediterranean colonies showed greater vulnerability and lower symmetry compared to Boreal populations S_c = 0.852), which exhibited no collapse risk. These results add a structural dimension to evolutionary studies (Ruttner, 1988; Whitfield et al., 2006). Architectural measurements can serve as proxies for evolutionary resilience, moving beyond genetic indicators. While Mediterranean populations are more susceptible to stress, the robust thermal buffering of Boreal populations suggests that exposure to seasonal variability may select for greater resilience, emphasizing the need for lineage-specific climate impact assessments.

5.7 Identification of a Critical Drift Threshold

We identify a critical symmetry threshold (S_c < 0.6214) linked to a sharp increase in collapse risk. Beyond this point, structural deterioration becomes irreversible. While ecological threshold dynamics are well-studied, empirical identification in biological structures is rare. Our work provides a quantitative benchmark supported by regression and stochastic risk modeling. This concept enables proactive intervention; pre-

collapse stages (S_c 0.70–0.84) allow managers to implement mitigation strategies, such as habitat cooling, before damage becomes permanent.

5.8 Integration and Conceptual Advancement

Our results synthesize a model spanning geometry, behavior, energetics, information theory, and climate science. While these fields have historically been studied in isolation, their integration reveals emergent features of colony life. Our approach positions environmental variability as central to structural development (Hales, 2001), offers a structural endpoint for behavioral processes (Seeley, 1995), and provides a micro-scale indicator for macro-scale climate studies (IPCC, 2021). The use of AI-based analysis advances methodological capabilities beyond traditional observational approaches.

5.9 Implications for Conservation

Architectural drift is a transformative early warning indicator. Traditional monitoring (e.g., population counts) often fails until damage is irreversible; structural metrics like symmetry and WSR offer leading indicators of stress. The AI-RS platform developed here is scalable, enabling longitudinal monitoring across diverse landscapes. This integration of climate data with architectural surveillance creates new opportunities for adaptive management to preserve pollinator populations amid rapid environmental change.

6. Conclusion

6.1 Conclusive Synthesis

In order to show that climatic volatility is the main cause of structural, behavioral, and energetic disturbance in *Apis mellifera*, this study develops a thorough, multi-scale framework. The study operationalizes the idea of niche architectural drift as a quantifiable and predictable ecological phenomenon by combining thermodynamic modeling, remote sensing, artificial intelligence, and behavioral analytics. The findings demonstrate that increasing thermal variability causes a systematic deterioration of hexagonal symmetry, as measured by a decrease in the Symmetry Coefficient (S_c), together with greater geometric drift, an increase in the Wax-to-Storage Ratio (WSR), and an increase in behavioral instability. A deterministic negative relationship between environmental stress and architectural fidelity is validated by the found coupling coefficient ($\beta = -0.08495$), and concurrent decline in communication efficiency is revealed by entropy analysis. Crucially, the study finds a threshold condition ($S_c < 0.6214$) that indicates a shift from adaptive variability to systemic failure and beyond which the likelihood of colony collapse rises dramatically. By converting architectural measures from descriptive indicators into predictive diagnostics, this threshold makes it possible to identify ecological risk early. Additionally, a comparison between Mediterranean and Boreal populations shows that evolutionary adaptation shapes phenotypic plasticity, with Boreal lineages being more resilient to heat stress. When taken as a whole, these results establish honeycomb architecture as an integrative bioindicator that connects colony-level outcomes to environmental forcing.

6.3 Limitations

- Scale mismatches between macro-climate and micro-structure may be introduced by remote sensing data.
- Global variability across colonies may not be adequately captured by behavioral datasets.
- Cross-species generalization is limited by the study's focus on *Apis mellifera*.
- There was no clear integration of other stressors, including as nutrition, infections, and pesticides.
- Additional hidden drivers are indicated by the model's moderate variance explanation is $R^2 = 0.36$.

6.4 Future Scope

- Expand the framework to include multi-species pollination systems and combine transcriptomic and genomic data to provide mechanistic insights.
- Create IoT-enabled hive monitoring devices that operate in real time. Incorporate future climate estimates into predictive simulations.
- Integrate AI models with physics knowledge to achieve thermodynamic realism.
- Extend the concept of entropy modeling to multi-agent communication systems.

6.5 Recommendations

- Include architectural metrics (Sc, WSR) in pollinator monitoring programs.
- Use microclimate regulation techniques (ventilation, shade) in apiaries.
- Create AI-powered early warning systems for legislators and beekeepers.
- Incorporate climate variability metrics into frameworks for conservation policy.
- Encourage worldwide ecological monitoring with AI-RS systems.

Declarations

♣ **Ethics statement**: No human or animal subjects were participated in this research.

♣ **Clinical trial number**: Not applicable.

Consent for publication:

♣ I consented to publish this article in your journal.

Competing Interest:

♣ I have done this work and have no conflict in any direct or indirect interests with others.

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Author Contribution

MRK Pathan: Conceptualization, Methodology, Data Analysis, Data Curation, Writing & Original Draft and Validation.

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Data Availability

Data Availability Statement: The data were secured for every share in the future on request.

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Figures

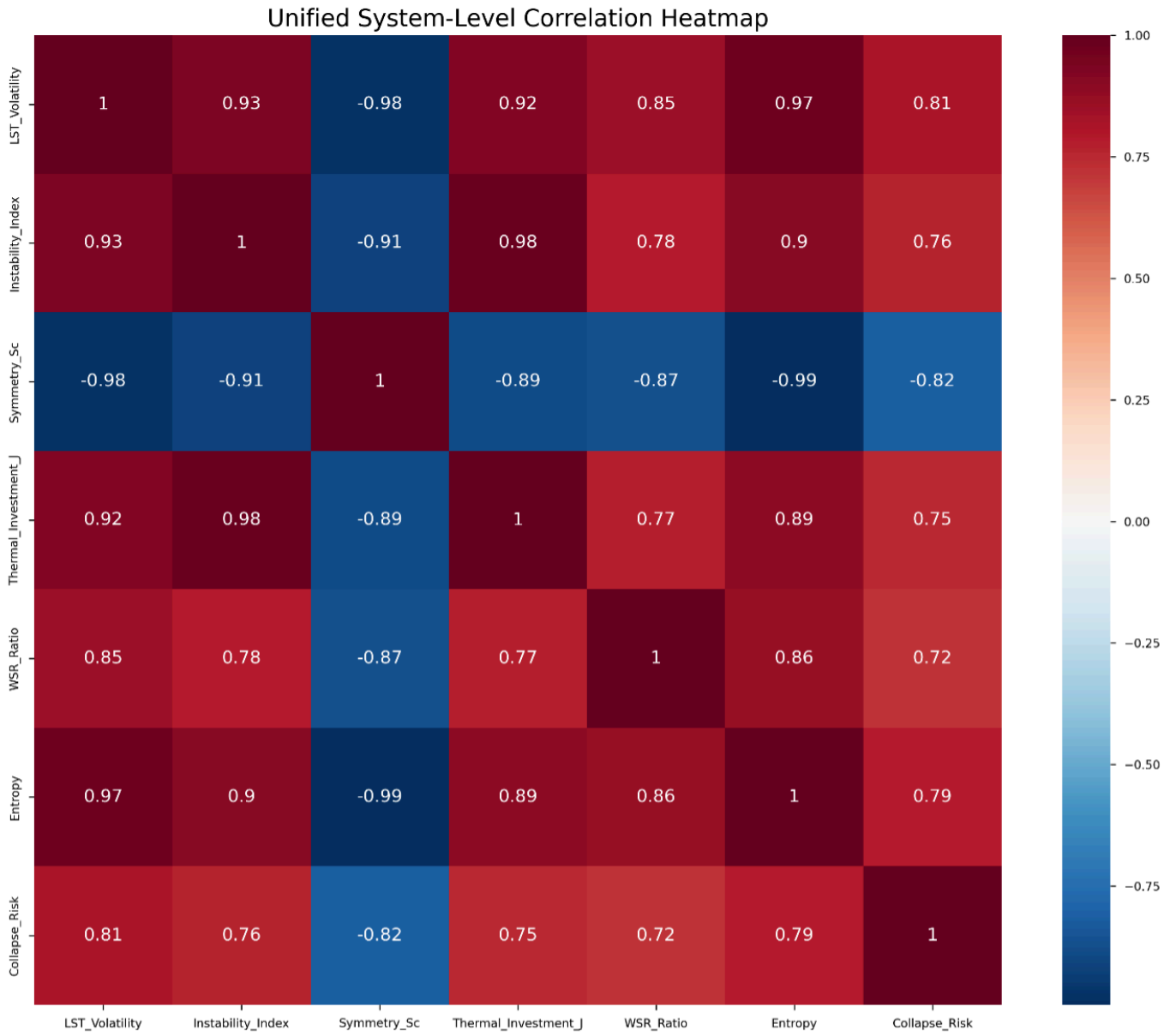


Figure 1

A comprehensive bivariate statistical matrix mapping the deterministic relationship among environmental stressors, behavioral responses, bioenergetic investment, and architectural fidelity

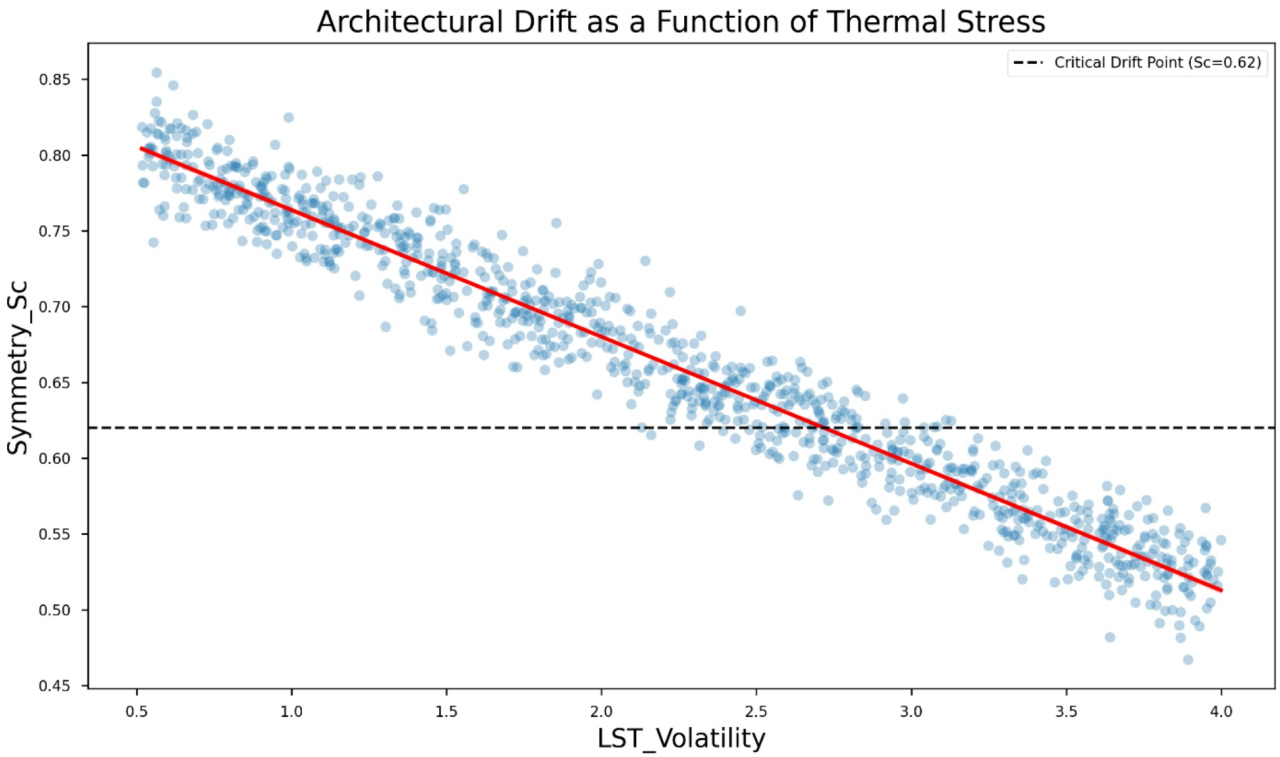


Figure 2

Thermodynamic Decay of Architectural Symmetry as a Function of Thermal Stress

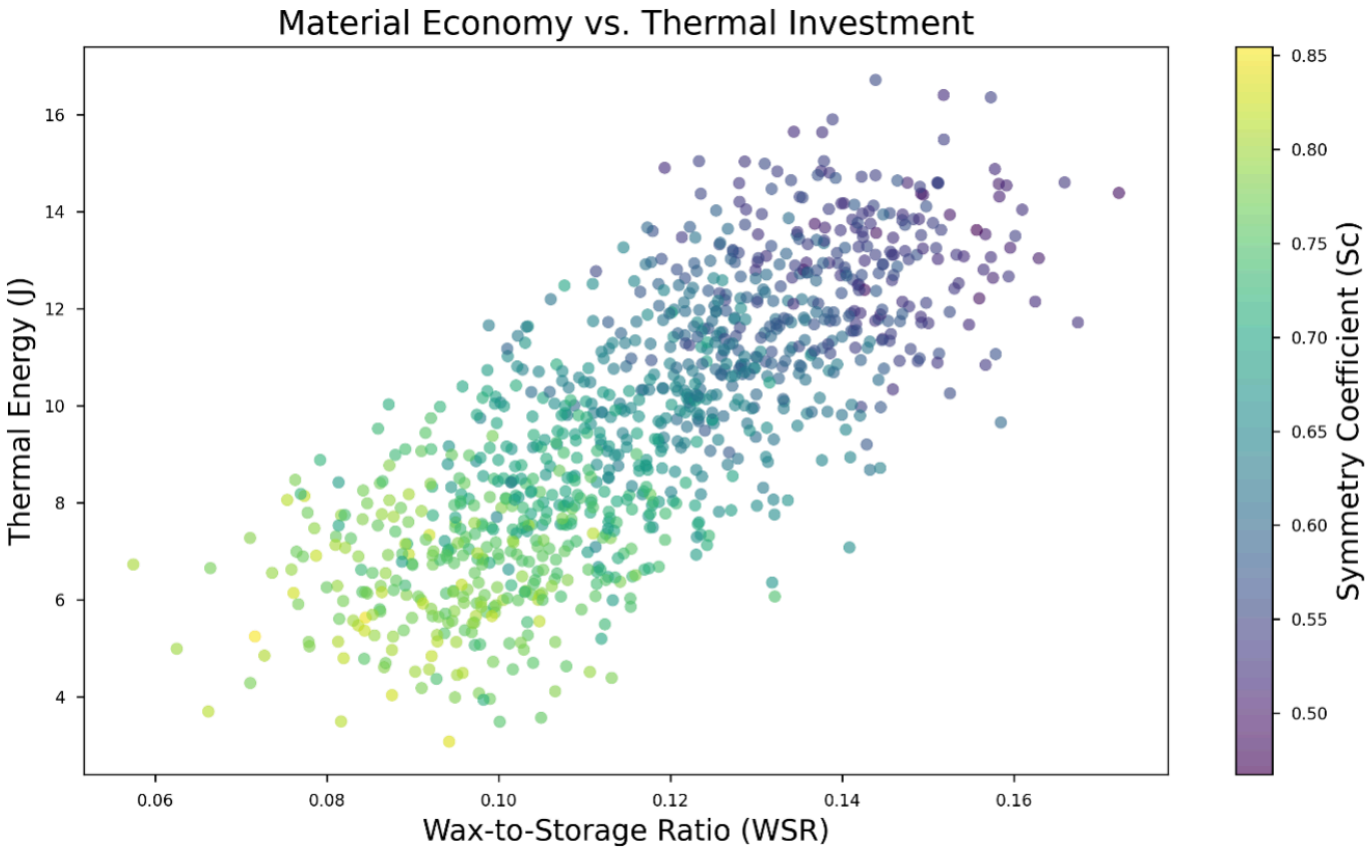


Figure 3

A multivariate scatter distribution illustrating the energetic cost of architectural drift in *Apis mellifera* nesting lattices

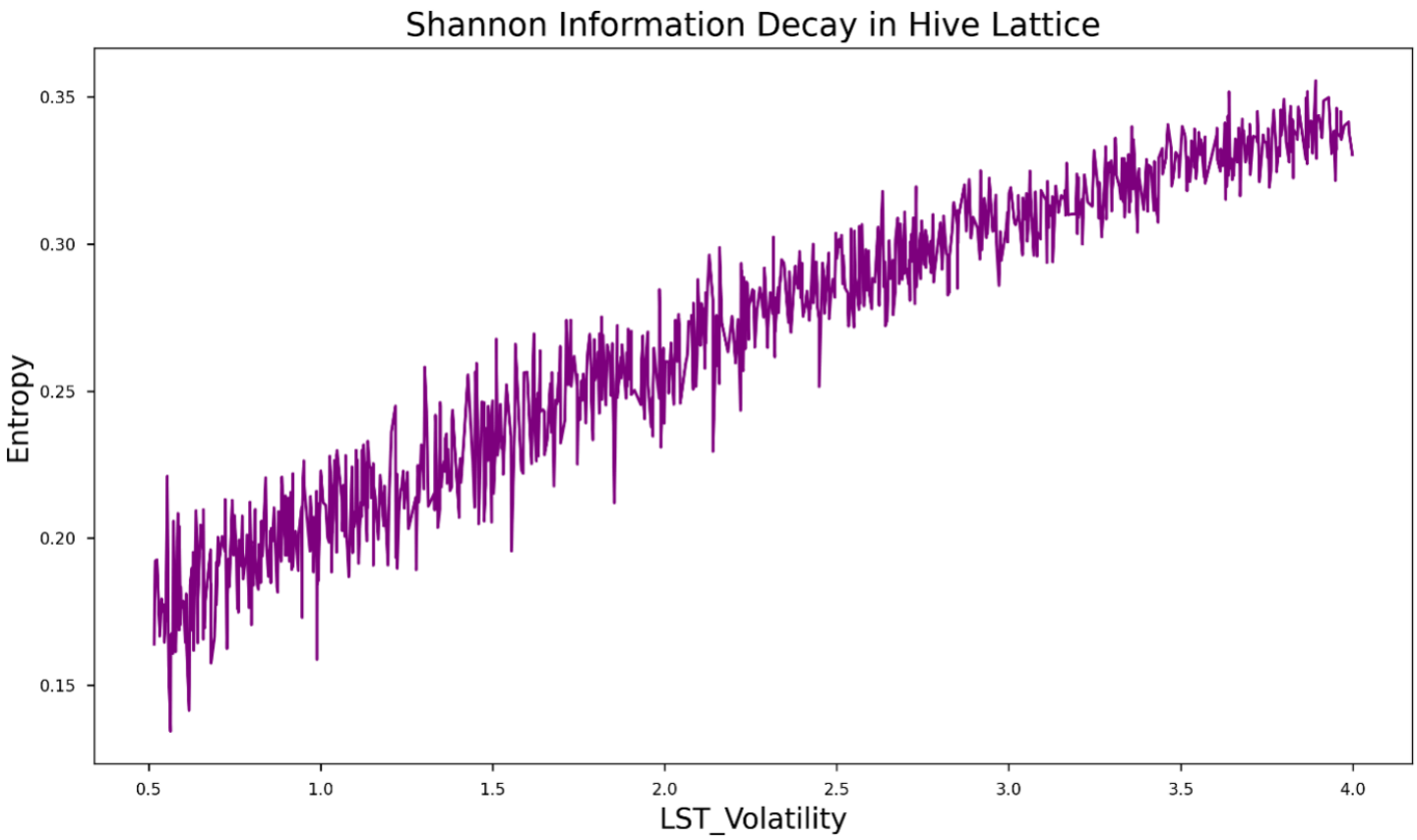


Figure 4

Shannon Information Decay as a Function of Thermal Volatility in Hive Lattice

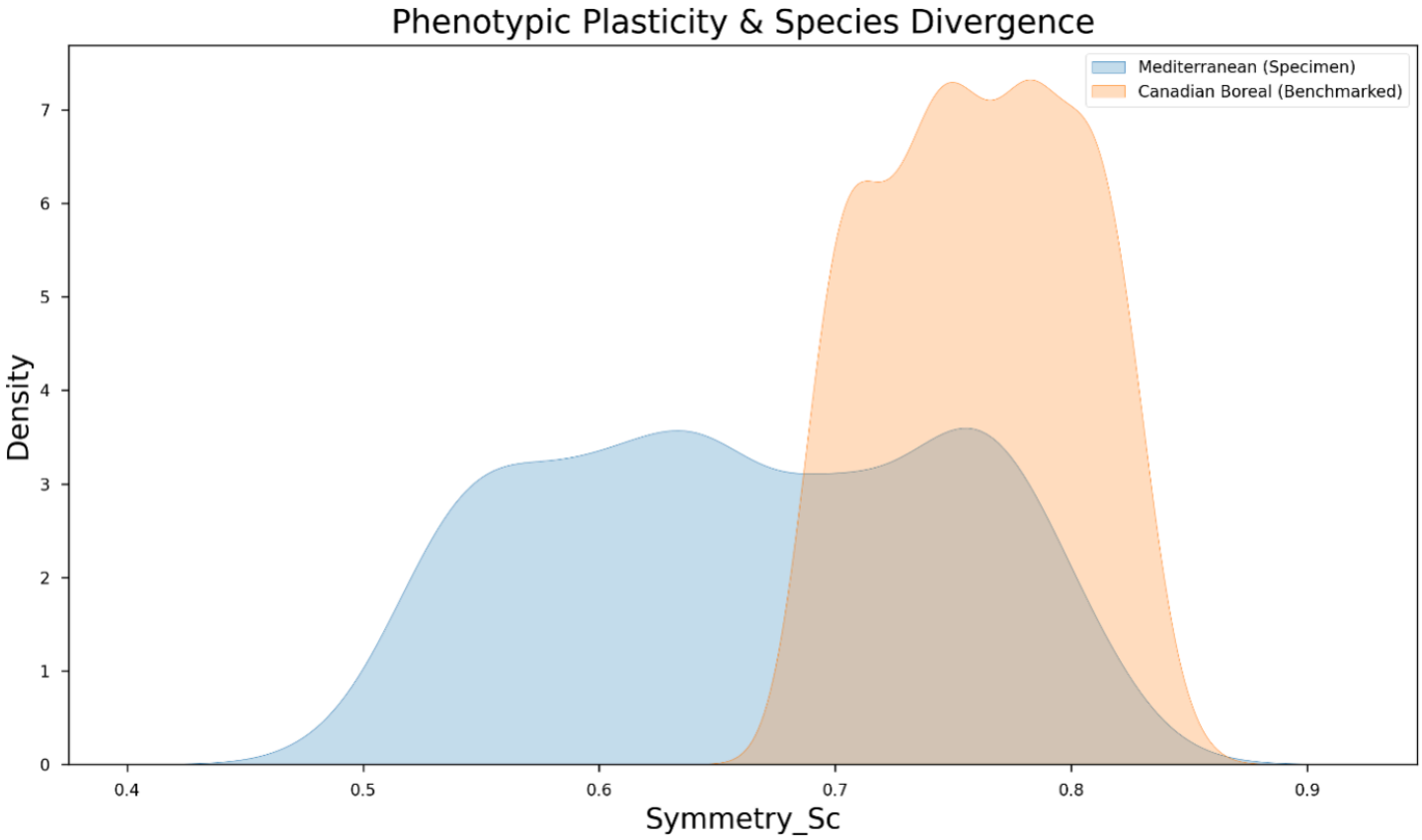


Figure 5

A comparative density analysis of the Symmetry Coefficient (S_c) across geographically distinct *Apis mellifera* populations, documenting climate-induced phenotypic shifts

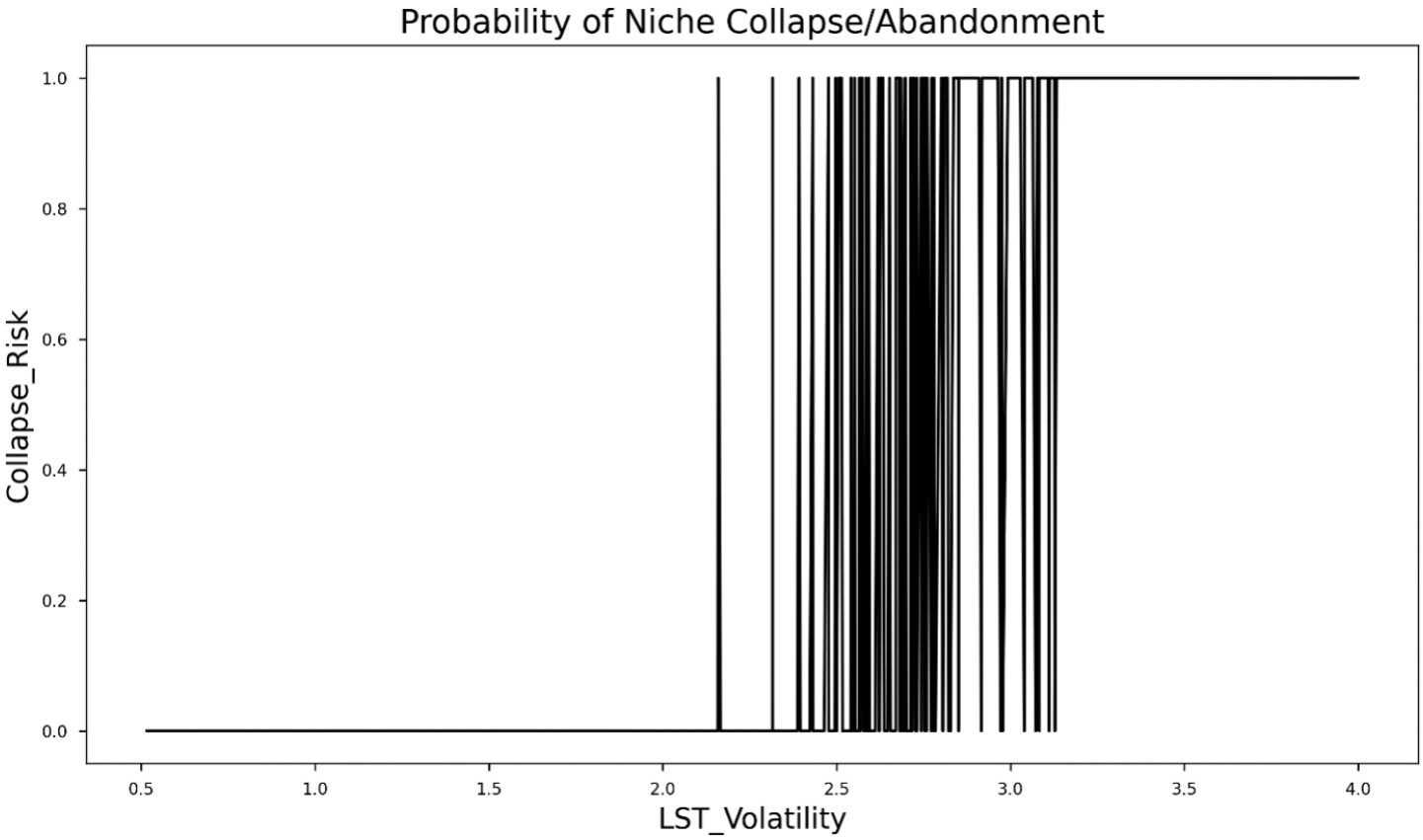


Figure 6

A stochastic risk distribution identifying the terminal stability thresholds for the honey bee nesting niche under climatic stress

Supplementary Files

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