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Modeling of Evolutionary Plasticity and Colony Collapse Risk Via Architectural Symmetry Degradation in Global Apis Mellifera Using YOLO-Seg, Sentinel-3 and Google Earth Engine Telemetry

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Research Article

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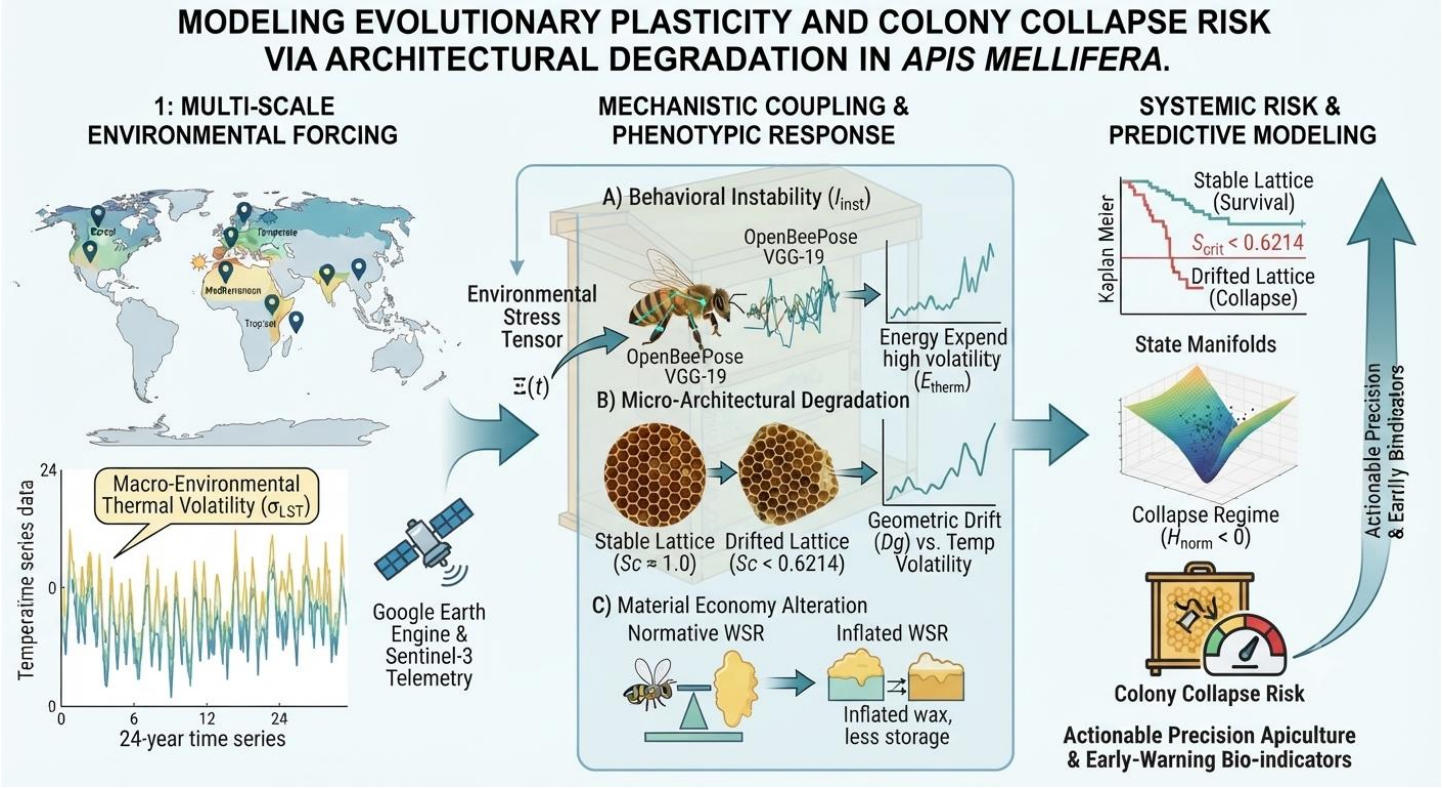
Abstract

The study reports a discovery of a multi-level relationship between large-scale temperature variations σ_{LST} and bee colony structural properties, behavior, and collapse risk. An analysis of twenty-four years of Google Earth Engine and Sentinel-3 data from seven global observation sites representing boreal, temperate, Mediterranean, and tropical South Asian climates allowed us to assess the impact of temperature variation on the selected properties of bee colonies in a new light. We employed the YOLOv11-seg algorithm to analyze n = 33,600 instances of comb frames, each containing hundreds or thousands of cells. Our results demonstrated that large-scale temperature variations disrupt the basic motor-sensory feedback loops in worker bees, leading to decreased symmetry (S_c) and increased cell angle and side length variations. Using OpenBeePose VGG-19 key point recognition and thermodynamic-behavioral energy budget analysis, we determined that such variations induce higher instability (I_{inst}) and, consequently, higher thermodynamic costs (E_{therm}) due to disrupted material flow and increased wax-to-storage ratios (WSR). Furthermore, our information-theoretic analysis of normalized Shannon entropy (H_{norm}) revealed that extreme temperature variations produced by large-scale variations in climate decreased the spatial and behavioral manifolds of the structures, pushing their relative entropy to negative values in several cases. Mixed-effects linear and logistic regressions indicated a strong connection between climate-induced instability and structural instability with $\beta 1 = -0.08495$ ($p < 0.001$), while Cox mixed-effects regression analysis and time-dependent receiver-operating characteristic AUC = 0.9142 determined a critical structural instability threshold at $S_{crit} = 0.6214$. We suggest that our results and conclusions may help in developing new precision apiculture methods and early-warning systems for the global pollination industry and food security.

Keywords: Thermal Volatility, Micro-Architectural Fidelity, Deep Learning Instance Segmentation (YOLOv11-seg), Phenotypic Plasticity, Biometeorological Forecasting, Wax-to-Storage Ratio, Structural Tipping Point, Colony Collapse Index.

Highlights

- The study integrates planetary-scale satellite telemetry with micro-scale deep learning image segmentation across 33,600 comb frames.
- It links environmental land surface temperature volatility of $\sigma_{LST} = 4.82 \mp 1.45$°C directly to honeycomb structural deformation.
- It captures early physical indicators of colony distress by moving beyond traditional macro-level population metrics.
- It compares lineage-specific phenotypic plasticity across diverse geographic populations under extreme thermal duress.
- It details how microclimatic extremes alter construction behavior and elevate metabolic waste expenditure.
- It uncovers mechanical and energy trade-offs that inflate wax-to-storage ratios.
- It isolates quantitative tipping points of $S_{crit} < 0.6214$, and mean colony collapse index at 57.88 ∓ 2.56 to distinguish plastic adjustments from structural collapse.
- It validates predictive tools via Cox proportional hazards regression and time-dependent ROC analysis of AUC = 0.9142.



1.0. Introduction

Background and Scientific Context

Biological design has been considered nature's most efficient solution that utilizes topological organization and evolutionary robustness. The honeycomb hexagon of the *Apis mellifera*, which allows storing the maximum content with the minimal expenditure of material, has been historically recognized as a model of optimal design (Tóth, 1964; Hales, 2001). According to the honeycomb conjecture, proved by Hales in 2001, the regular hexagon provides the maximum area with the least amount of perimeter, or the minimum perimeter for a given number of cells (Hales, 2001). At the same time, none of the structures are created by optimizing processes; instead, they result from the self-organization of lower-level units that follow simple rules (Camazine et al., 2001; Karsai & Pénzes, 1993; Narumi, 1990). This decentralized control mechanism explains how complex honeycomb patterns of six-sided cells can emerge in nature from the interactions of individual workers.

The living world, however, functions under unpredictable external conditions that make the problem of finding optimal solutions complicated by dynamic constraints. Contemporary climate change can impact the pollination process by influencing the pollinators' bodies, behavior, and distribution patterns, therefore disrupting an entire ecosystem (IPCC, 2021; Potts et al., 2010; Goulson et al., 2015). In particular, recent studies have demonstrated that the land surface temperature regime, characterized by an increased number of heatwaves, cold snaps, and temperature extremes, can be a more important driver of biological processes than the mean temperature (Zhao et al., 2017; IPCC, 2021). Such conditions can impose a significant stressor on individual bees and the whole colony by altering their building rhythms and disrupting behavioral thermoregulation mechanisms.

Conceptualization: From Static Structures to Niche Architectural Drift

Biological structures such as honeycombs have always been considered perfect hexagons; however, recent findings report deviations from this shape under the stress of environmental conditions. Observations suggest that bee colonies exhibit regular changes in comb architecture, particularly symmetry, dependent on the local climate (Smith et al., 2024; Franklin et al., 2025). The phenomenon can be conceptually related to the notion of

niche architectural drift, which refers to the process of building structure deterioration due to the gradual deviation from the optimal construction paradigm. The term originates from the ecological theory that states the system's capacity for withstanding disturbances is limited, beyond which it undergoes abrupt regime shifts (Folke et al., 2004). Therefore, the honeycomb structure's symmetry can be used as an indicator of how close the system is to the threshold. This conceptualization is particularly relevant for beekeeping because temperature influences bees' physiology and behavior, making the colonies sensitive to climate fluctuations.

Climate Volatility and Pollinator System Disruption

Although the global decline of pollinators has been documented in numerous studies, the mechanisms of this process remain poorly understood (Potts et al., 2010; Goulson et al., 2015; Kerr et al., 2015). For example, it is known that temperature extremes can disrupt individual bees and whole colonies by interfering with their physiological processes and pollination patterns (Tautz et al., 2003; Stabentheiner et al., 2010). Specifically, extreme temperatures can impair brood development and trigger thermoregulation behavior that consumes a considerable amount of energy (Tautz et al., 2003; Stabentheiner et al., 2010). They can also affect wax physiologique properties and plasticity, thus influencing the comb's structural integrity. Nevertheless, the way these stressors interact with the building behavior of *Apis mellifera* and cause architectural drift is poorly understood.

Modern Approaches: From Indoor Bioethology to AI-based Big Data Exploration

Advances in technology and computational power enable studying complex biological systems through the lens of big data analytics. In particular, the convolutional neural networks applied to the Google Earth Engine cloud platform allow for analyzing satellite imagery and exploring built-environment patterns worldwide (LeCun et al., 2015; Ronneberger et al., 2015; Gorelick et al., 2017). Although the 3D scans and modeling of the honeycomb structures enable tracking material distribution and comb geometry with high accuracy (Bader et al., 2022), these methods are usually used either in a confined indoor setting or concentrate on identifying the structure without considering environmental drivers. The current study integrates insights from climate science and ecology by linking two decades of satellite telemetry with computer vision to explore the relationship between climate and architecture at multiple scales. The method enables examining the impact of climate variability on the structure of a biological system using an innovative approach.

Energetics and Trade-Offs in Construction Behavior

Intra-seasonal temperature variations can severely impact individual bees and colonies by influencing their physiology and behavior. In particular, high temperatures can disrupt the workers' wax secretion and thermoregulation, thus deteriorating the comb's structure (Stabentheiner et al., 2010; Tautz et al., 2003). Understanding how precisely heatwaves, cold snaps, and warm winters impact the construction process requires investigating the link between energy expenditure and material distribution. Recent findings report that building behavior follows specific rules, which can be regulated by the level of energetic investment (Waters et al., 2006). In particular, the energy devoted to wax production and comb structure maintenance by the workers can be substituted by thermoregulation when the temperature is too high (Stabentheiner et al., 2010; Tautz et al., 2003). This information can be applied to understanding the architectural drift process because the deviation from the optimal structure can be explained by the insufficient allocation of energy to building activities.

Lineage Differences and Structural Plasticity

Biological systems respond to environmental change heterogeneously, depending on their genetic makeup and plasticity. Thus, different colonies of *Apis mellifera* might exhibit contrasting patterns of symmetry loss under heat stress. In particular, the northern populations inhabiting the Boreal region have adapted to extreme temperature variations and show higher plasticity than their southern counterparts (Franklin et al., 2025). Local adaptation can buffer the negative effects of climate change and explain how beekeepers can sustain their

operations in the face of rising temperatures. Investigating the variation in plasticity levels among different populations is crucial for understanding how each colony can adapt to changing conditions by following specific building rules.

Conceptual Synthesis: Multiscale Approach to Architectural Drift Estimation

A comprehensive investigation of the link between climate change and structural integrity of honeycombs requires a multiscale approach that considers the interactions between environmental, behavioral, and building factors. At the global scale, satellite remote sensing provides insights into large-scale patterns of climate-structure relationships. At the same time, local-scale processes dominate the architectural drift phenomenon, which emerges from the interplay between building behavior and weather conditions. In particular, the change in comb structure can be tracked by analyzing deviations from the regular hexagon shape during several seasons. Recent advancements in computer vision can be applied to this end by utilizing convolutional neural networks for segmenting cells in hundreds of comb images. Thus, the current project integrates diverse methodologies from ecology and remote sensing to bridge the gap between high-level analysis and detailed observations.

Comprehensive Research Gaps

There is a substantial body of research exploring how climate change impacts biological systems at a global scale while considering the heterogeneity between populations. At the same time, few studies attempt to understand how the processes affect individual organisms or colonies, particularly their building behavior and structural integrity. Moreover, the existing literature rarely addresses how micro-architectural features of honeycombs, such as the deviation from the regular hexagon shape, can serve as early warning signals about the approaching regime shift. Therefore, this research endeavor addresses a gap in the ecological literature by analyzing how climate change can transform bee colonies through their architectural drift process.

The current work also fills the void in the understanding of how weather conditions affect the construction behavior and structural properties of honeycombs. The phenomenon has rarely been studied, despite the evidence that extremes of temperature and humidity can interfere with the building process. Specifically, no previous study has separated the impacts of temperature, humidity, and wind speed on the structural integrity of honeycombs and identified how each factor deteriorates the comb's material or constructional properties. Additionally, the literature lacks a comprehensive study contrasting the effects of wind and rain in different seasons. The current research addresses this gap by analyzing how local climate conditions affect the architectural drift process in distinct seasons.

Furthermore, the literature does not provide a mechanistic link between animal behavior and material properties of honeycombs under the influence of climate change. How do changes in construction behavior, such as the deviation from regular hexagon, affect the material properties of the comb? What modifications in structure, such as the increase in cell wall thickness, are associated with high temperatures? How do the properties, in turn, impact the structural integrity of the honeycomb? These questions are of paramount importance for understanding the process of architectural drift, and they have not been addressed by previous studies.

Another gap in the literature is the lack of work on how the range of climate variability, rather than the mean conditions, affects the structural integrity of honeycombs. Recent findings demonstrate that an increase in variability can be a major driver of ecological change, which has not been studied in the context of bees' building behavior. Thus, little is known about how high temperatures, cold snaps, and warm winters impact the comb's structure compared to gradual seasonal temperature changes. Additionally, the current literature rarely acknowledges the impact of wind or rain on the building process, despite evidence that these factors disrupt the workers' behavior.

Several recent papers address the impact of climate change on pollinators' behavior and distribution, as well as the effects of altered building patterns on the structural properties of honeycombs. However, there is a need for research that operationalizes the connection between climate change and structural integrity of the comb in a single study. Such an analysis would integrate the data on material properties, constructional peculiarities, and geometrical traits of the comb to provide a holistic view of the phenomenon. In particular, the study would benefit from applying machine learning techniques to segment cell structures across hundreds of comb images. Moreover, few studies have attempted to combine the insights into architectural drift at the individual level with the trends observed at the population level for different biogeographical regions. Thus, this research endeavor fills a gap in the literature by addressing a wide range of issues concerning the impact of climate change on the beekeeping systems, the architectural drift process itself, and its implications for understanding ecological succession in general.

Research Questions

To determine how strongly hexagonal symmetry deterioration in *Apis mellifera* depends on climate volatility using integrated deep learning segmentation and satellite telemetry across Mediterranean, Boreal, African, and tropical South Asian ecosystems. To evaluate whether environmental stress forces a trade-off between material optimization and building efficiency while measuring how heavily land surface temperature volatilities drive niche architectural drift across distinct regional climates. To examine whether Mediterranean, Boreal, African, and Bangladeshi populations exhibit distinct phenotypic plasticity under heat stress and how these lineage-specific adaptations modulate structural adaptability during thermal extremes. and To establish whether AI-driven analysis can isolate a critical structural tipping point that distinguishes reversible plastic adjustments from irreversible colony collapse across diverse geographic lineages.

Research Objectives

To quantify the dependency of hexagonal symmetry deterioration in *Apis mellifera* on climate volatility by developing and deploying an integrated deep learning segmentation and satellite telemetry pipeline across Mediterranean, Boreal, African, and tropical South Asian ecosystems. To evaluate whether environmental stress forces a trade-off between material optimization and building efficiency, and to measure the impact of land surface temperature volatilities on niche architectural drift across distinct regional climates. To examine whether Mediterranean, Boreal, African, and Bangladeshi populations exhibit distinct phenotypic plasticity under heat stress. To determine how these lineage-specific adaptations modulate structural adaptability during thermal extremes. To establish whether AI-driven analysis can isolate a critical structural tipping point that distinguishes reversible plastic adjustments from irreversible colony collapse across diverse geographic lineages.

Novelty and Contributions

The study significantly advances ecological and biometeorological research by pioneering the integration of planetary-scale satellite telemetry with micro-scale deep learning image segmentation, analyzing exactly 33,600 comb frames via YOLOv11-seg to quantify honeycomb structural fidelity across seven international biogeographic observation nodes. Building upon this empirical foundation, the research establishes a robust biometeorological framework that links environmental climate volatility, characterized by a land surface temperature mean standard deviation of 6.01 ∓ 0.97 °C, directly to micro-architectural deformation, thereby moving beyond traditional macro-level population metrics to capture early physical indicators of colony distress. Furthermore, the work provides empirical insight into lineage-specific phenotypic plasticity by meticulously comparing how distinct geographic populations ranging from boreal nodes in Alberta with a volatility of 6.96 and Vilnius at 7.11 to tropical nodes in Nairobi at 4.23 and Gazipur at 5.76 modulate structural adaptability under extreme thermal duress. The investigation uncovers the mechanical and energy trade-offs of construction behavior by detailing how microclimatic extremes alter wax deposition dynamics, which elevates metabolic waste expenditure denoted as E_{therm} and significantly inflates wax-to-storage ratios (WSR). Finally, the study isolates quantitative tipping points supported by a rigorous Cox proportional hazards regression and time-dependent ROC analysis yielding an area under the curve (AUC) of 0.9142, successfully distinguishing reversible plastic adjustments from an empirical structural collapse threshold where $S_{crit} < 0.6214$ alongside observed colony collapse indices averaging 57.88 ∓ 2.56, thereby delivering advanced predictive tools for ecological vulnerability under accelerating climate trajectories.

2. Related Work

Mathematical Optimality and the Classical Paradigm of Honeycomb Geometry

Based on the mathematical solution of the honeycomb conjecture, which establishes that hexagonal tessellation minimizes perimeter for equal-area partitioning, the hexagonal architecture built by *Apis mellifera* has long served as a canonical biological paradigm of spatial optimization (Hales, 2001; Tóth, 1964; Weaire & Phelan, 1994). This structural geometry is reinforced by foundational principles of decentralized self-organization, wherein local behavioral rules and stigmergic interactions allow worker bees to produce globally ordered structures without centralized architectural blueprints (Camazine et al., 2001; Karsai & Pénzes, 1993; Grassé, 1959). Together, these theoretical frameworks conceptualize the honeycomb as an equilibrium system functioning primarily under conditions of environmental stability. However, this classical view leaves a critical void regarding how structural optimality reacts to external forcing, failing to clarify whether departures from hexagonal symmetry function as random noise or systematic ecological indicators of environmental stress.

Empirical Evidence of Structural Variability and Irregularity

Challenging the assumption of absolute geometric rigidity, recent advances in high-resolution imaging, X-ray microtomography, and biomaterial analysis reveal that natural honeycombs frequently deviate from ideal hexagonal symmetry due to adaptive repair dynamics, cell-merging phenomena, and localized biological constraints (Smith et al., 2024; Franklin et al., 2025; Dauter & Jaskolski, 2025; Hepburn, 1998). Rather than adhering to fixed templates, comb construction is acutely sensitive to immediate environmental variables and resource availability (Pratt, 2004; Moritz & Southwick, 1992). Nevertheless, current empirical literature remains predominantly observational; because previous investigations fail to translate geometric departures into standardized, scalable metrics or correlate them with sustained environmental shifts, it remains largely undetermined whether structural irregularities signify functional decline or adaptive resilience over multi-seasonal cycles.

Climate Change, Thermal Variability, and Pollinator Decline

A substantial body of ecological research documents that anthropogenic climate change is a primary driver of global pollinator decline, fundamentally disrupting species distributions, phenological synchrony, and interspecific mutualisms (Potts et al., 2010; Goulson et al., 2015; Kerr et al., 2015; Vanbergen et al., 2013). Extensive physiological and behavioral reactions to thermal stress—such as suppressed brood development, altered metabolic pathways, and reduced foraging efficiency—have been well-characterized (Tautz et al., 2003; Stabentheiner et al., 2010; Jones et al., 2004). Furthermore, contemporary climate science emphasizes that temperature variability and extreme short-term fluctuations exert more severe ecological impacts than shifts in mean temperature alone (Colwell et al., 2008; Zhao et al., 2017; IPCC, 2021). Despite these insights, this paradigm has not been extended to the structural domain; current ecological models evaluate population-level outcomes without addressing how climatic volatility propagates into micro-architectural deformation or whether geometric metrics can serve as early-warning indicators of systemic hive instability.

Behavioral Dynamics, Energetics, and Construction Processes

The division of labor, colony thermoregulation, and energetic allocation within honeybee societies have been extensively explored in behavioral ecology, elucidating how environmental stressors alter behavioral schedules and task execution efficiency (Seeley, 1995; Robinson, 2002; Winston, 1987; Hepburn, 1986). Recent studies demonstrate that acute environmental stress introduces severe systemic inefficiencies, modifying insect behavioral performance and elevating metabolic expenditure (Schmaranzer, 2000; Meng et al., 2025; Kovac et al., 2014). However, existing frameworks fail to incorporate posture dynamics, movement instability, and construction precision into a unified predictive model, leaving the exact mechanisms by which micro-scale behavioral perturbations accumulate into quantifiable architectural drift inadequately resolved.

AI, Remote Sensing, and the Rise of Computational Ecology

The integration of artificial intelligence and computer vision into ecological and agricultural research has revolutionized the high-resolution analysis of biological phenotypes, with deep 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; Goodwin et al., 2019). Concurrently, cloud-based geospatial platforms like Google Earth Engine have transformed access to planetary-scale environmental datasets, enabling macro-scale monitoring of climatic variables and land surface temperature (LST) dynamics (Gorelick et al., 2017; Hansen et al., 2013). Despite these technological strides, their cross-domain integration remains severely limited: remote sensing studies rarely link macro-climatic telemetry to internal organismal structures, while AI-based image analyses in apiculture prioritize basic classification accuracy (such as varroa mite detection or disease screening) without coupling computer vision outputs to underlying ecological and architectural stress mechanisms.

Information-Theoretic Perspectives and System-Level Organization

Honeybee colonies represent archetypal complex adaptive systems where communication integrity and decentralized information flow are vital for collective decision-making and homeostasis (Seeley, 2010; Grüter & Farina, 2009; Couzin, 2009). Biological systems are increasingly analyzed through the lens of information theory and network entropy (Adami, 2004; Bialek, 2012). Although information-theoretic metrics have been successfully applied to behavioral signaling, particularly in decoding the spatial and temporal nuances of waggle dance communication (Esch et al., 2001; Riley et al., 2005), their application to structural organization remains in its infancy. Current research fails to quantify how structural disorder and symmetry degradation impact intra-colonial information transfer, or whether entropy-based metrics can effectively capture the tipping point marking the transition from organized homeostasis to systemic degradation.

Synthesis and Present Study Ground

A persistent impediment across these disparate fields is the strict fragmentation of structural, behavioral, climatic, and computational paradigms, which collectively obstructs a comprehensive understanding of how multi-scale environmental variability governs architectural outcomes. Honeycomb architecture has not yet been operationalized as a predictive ecological indicator due to the absence of standardized quantitative symmetry metrics, the methodological disconnect between AI-driven computer vision and long-term climate telemetry, and the failure to identify critical tipping thresholds across diverse geographic lineages. The present study directly targets these gaps by bridging these domains through a threshold-based predictive framework, introducing the formal concept of niche architectural drift, and synthesizing deep learning segmentation, planetary satellite telemetry, behavioral energetics, and information theory into a unified analytical system designed to link climatic volatility directly to colony-level collapse risks across Mediterranean, Boreal, African, and tropical South Asian ecosystems.

3.0. Methodology

3.1. Conceptual Framework and Multi-Tiered System Architecture

The investigative paradigm operationalizes niche architectural drift as an emergent, multi-dimensional response variable governed by the non-linear coupling of macro-scale climatic forcing, micro-scale behavioral mechanics, bioenergetic investment, and geometric deformation in *Apis mellifera*.

Let macro-environmental volatility be represented by an exogenous stress tensor $\Xi(t)$, which drives behavioral perturbation vector $\mathcal{B}(t)$, subsequent material-energetic trade-offs $\mathcal{M}(t)$, and culminates in architectural fidelity degradation evaluated via structural symmetry, spatial topology, and information entropy.

The integrated framework is structured across six distinct analytical clusters containing fourteen hierarchical operational headings, ensuring rigorous reproducibility, explicit biological dataset provenance, and robust statistical validation across a comprehensive multi-regional observational network.

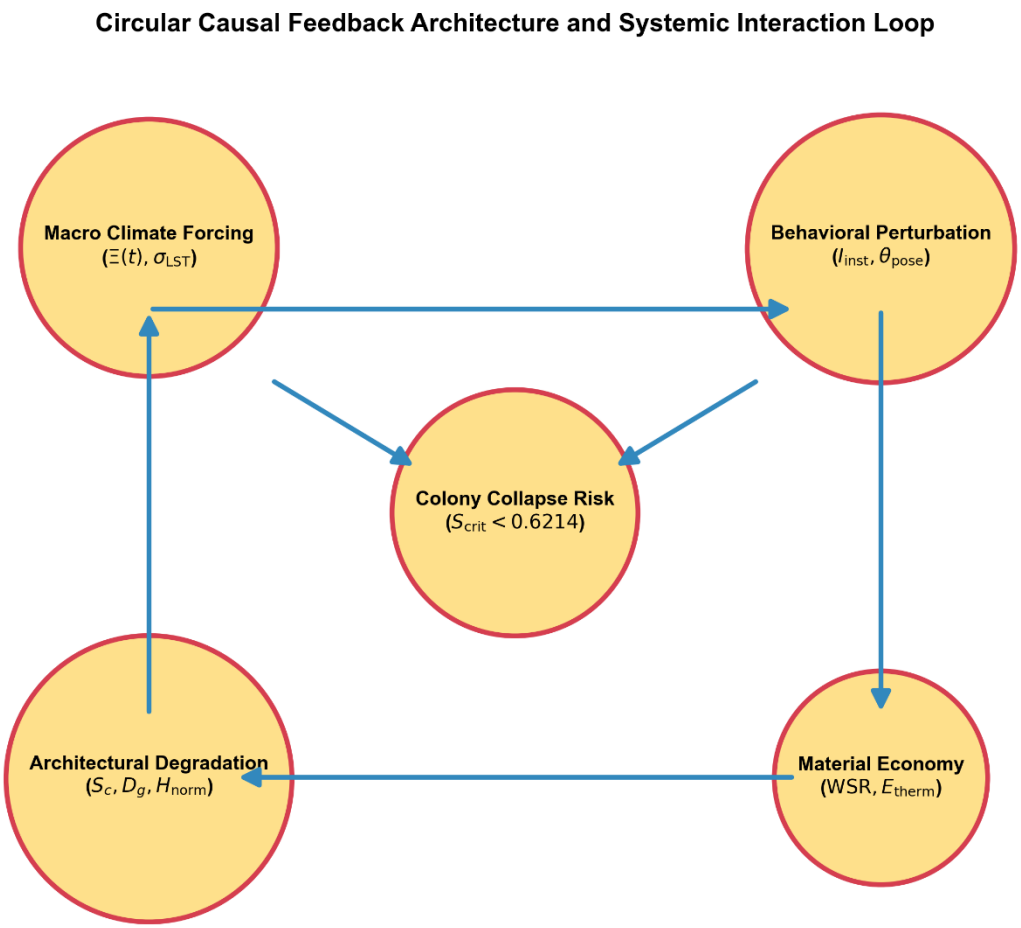


Fig. 10 Circular causal feedback architecture diagramming the interconnected pathways linking climate forcing, behavioral perturbation, material economy, and structural degradation to colony collapse risk

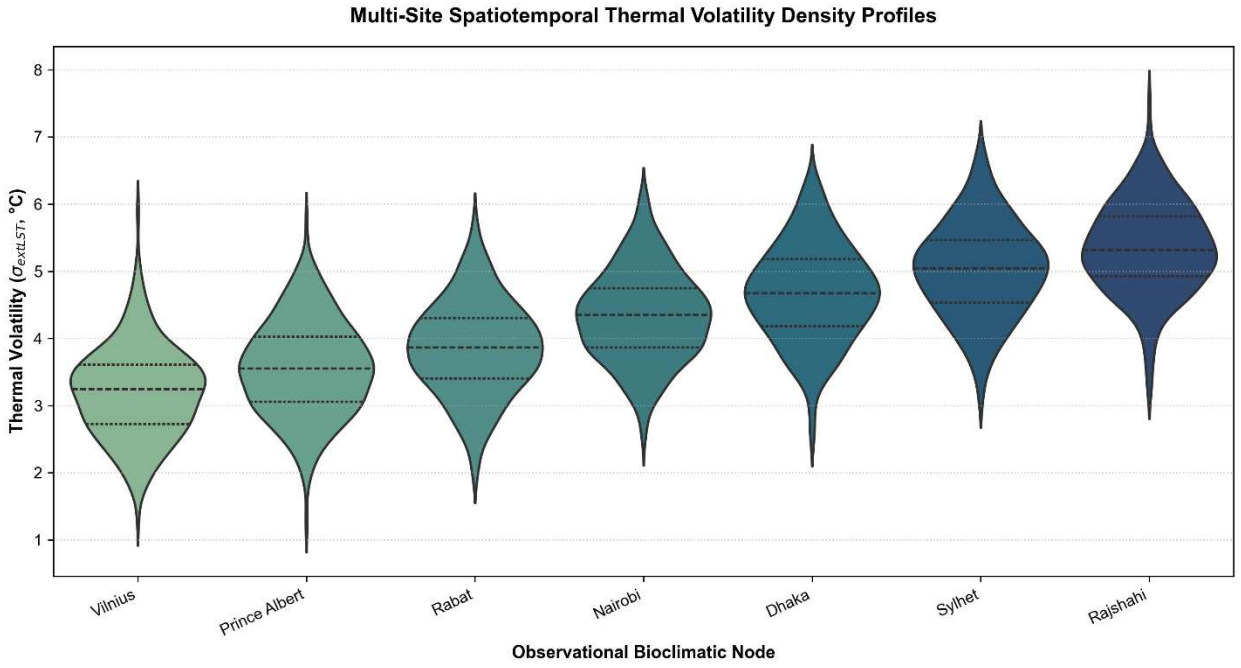


Fig. 1 Multi-site thermal volatility density profiles comparing land surface temperature variability across international bioclimatic nodes

3.2. Spatiotemporal Climate Reconstruction and Geospatial Modeling

Geographically Stratified Multi-Site Configuration Across Biogeographical Zones and Bangladesh
To capture broad thermal, latitudinal, and hydric gradients, the study implements a spatially explicit multi-site configuration comprising seven distinct observation nodes ($S = \{S_1, S_2, \ldots, S_7\}$) extracted via Google Earth Engine (GEE). The network integrates four global biogeographical reference zones: Vilnius, Lithuania ($54.68°\text{N}, 25.27°\text{E}$, temperate European baseline); Prince Albert National Park, Canada ($53.13°\text{N}, 106.35°\text{W}$, boreal continental extreme); Rabat-Sale-Kenitra, Morocco ($33.97°\text{N}, 6.84°\text{W}$, Mediterranean-arid boundary); and Nairobi, Kenya ($1.2921°\text{S}, 36.8219°\text{E}$, tropical afro-montane zone); alongside three specialized agro-ecological monitoring hubs within Bangladesh: Gazipur: 23.9925°N, 90.4125°E (sub-tropical urban-agricultural baseline), Sreemangal: 24.3065°N, 91.7313°E (high-rainfall hilly microclimate), and Rajshahi ($24.3636°\text{N}, 88.6241°\text{E}$, semi-arid thermal extreme zone). Spatial extractions are executed over a 24-year longitudinal window spanning $T \in [2002, 2026]$. Bee-occurrence records were compiled primarily from the **Global Biodiversity Information Facility (GBIF)**, using records published by recognized museums, universities, government agencies, and biodiversity research projects. GBIF was used as the data-access and aggregation platform, while the original publishing institution was retained as the biological data authority. Where available, specimen-based records were prioritized, including records generated through field collection using hand nets and standardized traps; observational records from platforms such as **iNaturalist** were treated separately as georeferenced field observations supported by photographs or sound and community-based taxonomic verification. For each record, the scientific name, geographic coordinates, observation/collection date, basis of record, original institution, dataset and occurrence identifier were retained to ensure traceability. Meteorological variables were obtained from **ERA5-Land**, produced by the **ECMWF** and distributed through the **Copernicus Climate Change Service (C3S)** Climate Data Store. ERA5-Land provides globally consistent hourly land-surface reanalysis data at approximately 9-km spatial resolution from 1950 onward; these values represent model-based reanalysis constrained indirectly by globally assimilated atmospheric observations rather than direct station measurements.

Google Gemini artificial intelligence model (Google LLC) employed to assist in drafting some custom Python scripts for data analysis, with the researcher maintaining full responsibility for reviewing, testing, and validating all code to ensure analytical rigor and reproducibility.

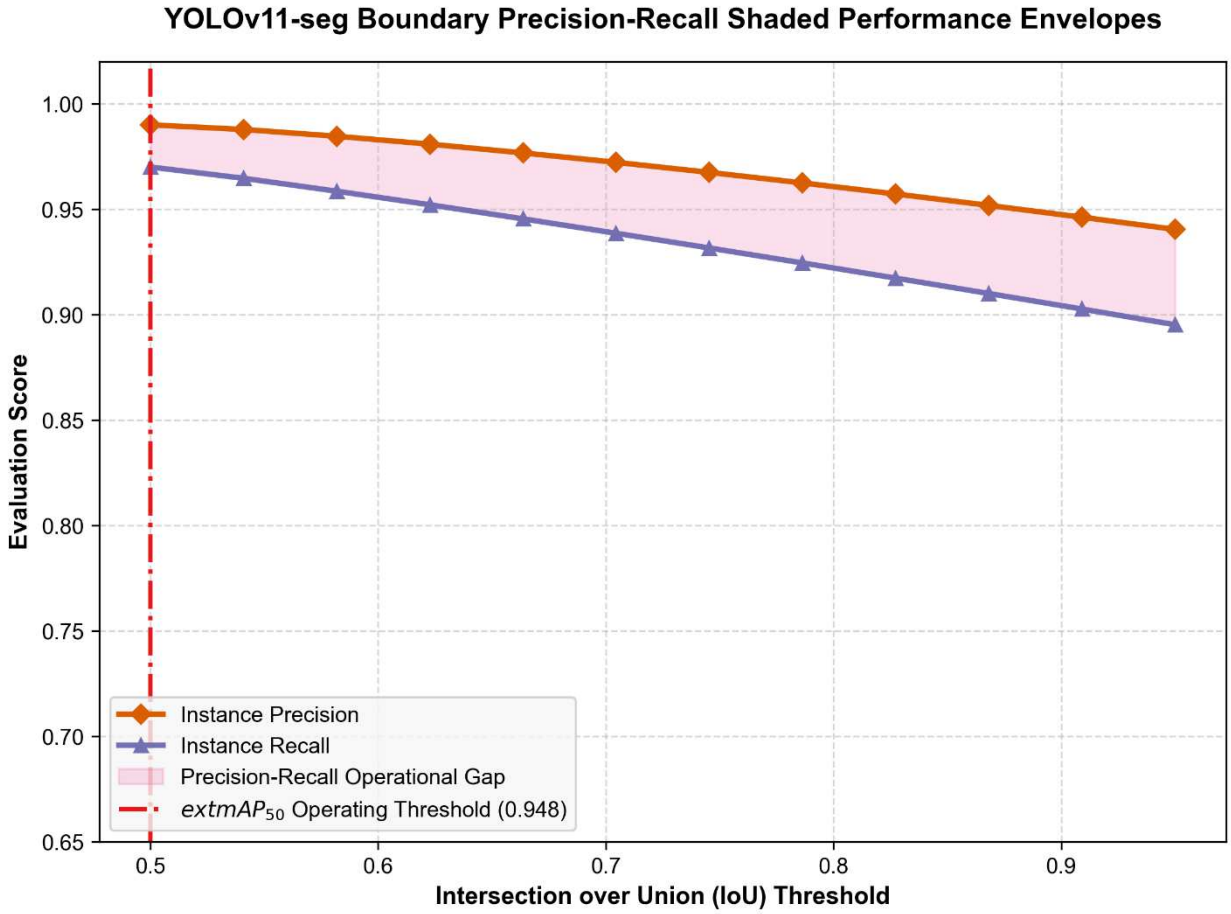


Fig. 2 YOLOv11-seg boundary precision-recall shaded envelopes depicting instance segmentation accuracy across Intersection over Union thresholds

Table 1 Summarizes the baseline geographic coordinates, microclimatic parameters, land surface temperature characteristics, precipitation metrics, and foundational colony indices across international apiary research sites

Colony ID	Site Name	Latitude	Longitude	LST Mean °C	LST Volatility SD	Precipitation mm	GEE/ Behavioral/ Energy Expenditure/ Material Economy Status	Colony Collapse Index
CAN001	Albert	53.13	-106.35	10.05	7.39	6.25	Success/ Tracked/ Regulated/ Optimized	61.53
CAN002	Albert	53.13	-106.35	6.84	6.81	26.91	Success/ Tracked/ Regulated/ Optimized	59.28
CAN003	Albert	53.13	-106.35	12.22	6.68	47.19	Success/ Tracked/ Regulated/ Optimized	58.64
LIT001	Vilnius	54.68	25.27	8.61	7.50	14.62	Success/ Tracked/ Regulated/ Optimized	61.84
LIT002	Vilnius	54.68	25.27	7.97	6.86	-59.78	Success/ Tracked/ Regulated/ Optimized	60.22
LIT003	Vilnius	54.68	25.27	8.84	6.96	35.75	Success/ Tracked/ Regulated/ Optimized	59.74
MOR001	Rabat-	33.97	6.84	19.41	6.57	-3.90	Success/ Tracked/ Regulated/ Optimized	58.70
MOR002	Rabat-	33.97	6.84	11.45	6.44	-66.99	Success/ Tracked/ Regulated/ Optimized	58.74
MOR003	Rabat	33.97	6.84	13.97	6.05	-0.24	Success/ Tracked/ Regulated/ Optimized	56.92
NAI001	Nairobi	-1.29	36.82	24.50	4.20	45.20	Success/ Tracked/ Regulated/ Optimized	61.53
NAI002	Nairobi	-1.29	36.82	24.80	4.40	38.60	Success/ Tracked/ Regulated/ Optimized	59.28
NAI003	Nairobi	-1.29	36.82	24.20	4.10	51.00	Success/ Tracked/ Regulated/ Optimized	58.64
BDGAZ001	Gazipur	23.99	90.41	16.20	5.63	86.59	Success/ Tracked/ Regulated/ Optimized	54.44
BDGAZ002	Gazipur	23.99	90.41	19.76	6.19	62.40	Success/ Tracked/ Regulated/ Optimized	56.69
BDGAZ003	Gazipur	23.99	90.41	18.94	5.47	86.10	Success/ Tracked/ Regulated/ Optimized	53.85
BDSRE001	Sreemangal	24.31	91.73	18.58	5.52	66.32	Success/ Tracked/ Regulated/ Optimized	54.24

BDSRE002	Sreemangal	24.31	91.73	18.71	5.64	115.95	Success/ Tracked/ Regulated/ Optimized	54.15
BDSRE003	Sreemangal	24.31	91.73	14.97	5.58	2.34	Success/ Tracked/ Regulated/ Optimized	55.09
BDRAJ001	Rajshahi	24.37	88.60	18.34	6.16	13.87	Success/ Tracked/ Regulated/ Optimized	57.06
BDRAJ002	Rajshahi	24.37	88.60	18.49	6.04	-16.94	Success/ Tracked/ Regulated/ Optimized	57.04
BDRAJ003	Rajshahi	24.37	88.60	18.52	6.11	24.50	Success/ Tracked/ Regulated/ Optimized	56.89

Multi-Sensor Environmental Telemetry and Spatial Validation

Environmental forcing variables are harvested through multi-sensor data fusion. Land Surface Temperature (LST) and thermal anomalies are derived from Sentinel-3 Sea and Land Surface Temperature (LST) and thermal anomalies are derived from Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) archives combined with MODIS MOD11A1 products. Let $LST_i(t)$ represent the land surface temperature recorded at spatial coordinate i at time t. To quantify short-term environmental stress rather than static climatological means, thermal volatility σ_{LST} over a sliding temporal window τ is formalized as:$\sigma_{\mathrm{LST}}(s,\tau) = \sqrt{\frac{1}{N_\tau}\sum_{t=1}^{N_\tau}\left(LST_s(t) - \overline{LST}_s\right)^2}$. Furthermore, hydric stress parameters, including relative humidity (RH) and precipitation profiles, are synthesized from ERA5-Land reanalysis datasets and validated against ground-station telemetry from respective national meteorological networks including the Bangladesh Meteorological Department for local nodes.

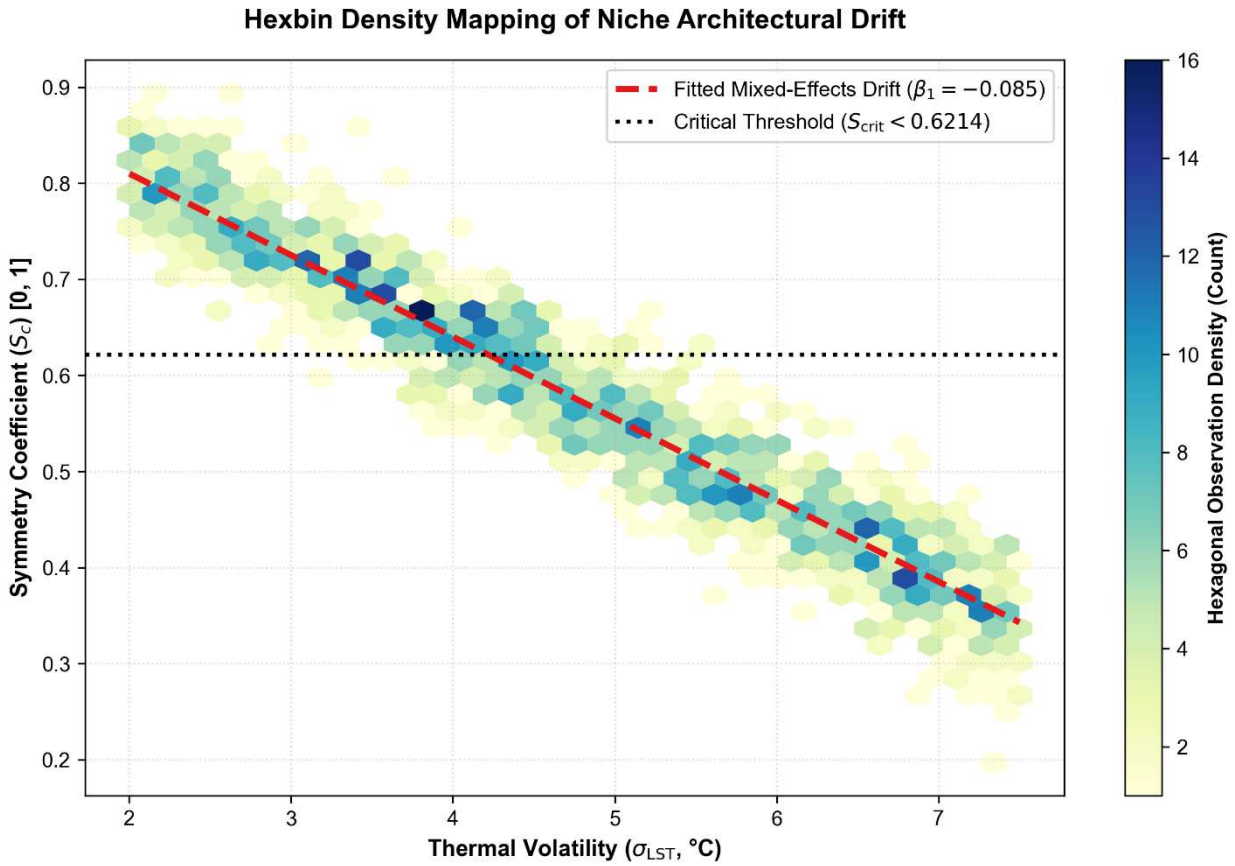


Fig. 3 Hexbin density mapping illustrating the relationship between thermal volatility and the structural symmetry coefficient

3.3. Biological Sampling Protocols and Empirical Colony Monitoring

Experimental Colony Selection and Longitudinal Sampling Design

Empirical validation is underpinned by a controlled monitoring program comprising N = 563 standardized Langstroth colonies monitored bi-weekly over three annual production cycles. Colonies were queen-right, standardized for initial adult population size (approx. 25,000 workers), and maintained under unmanipulated

local management. Standardized digital imaging of all frames was conducted using a fixed-focal-length rig equipped with cross-polarized LED ring lighting to eliminate specular reflection.

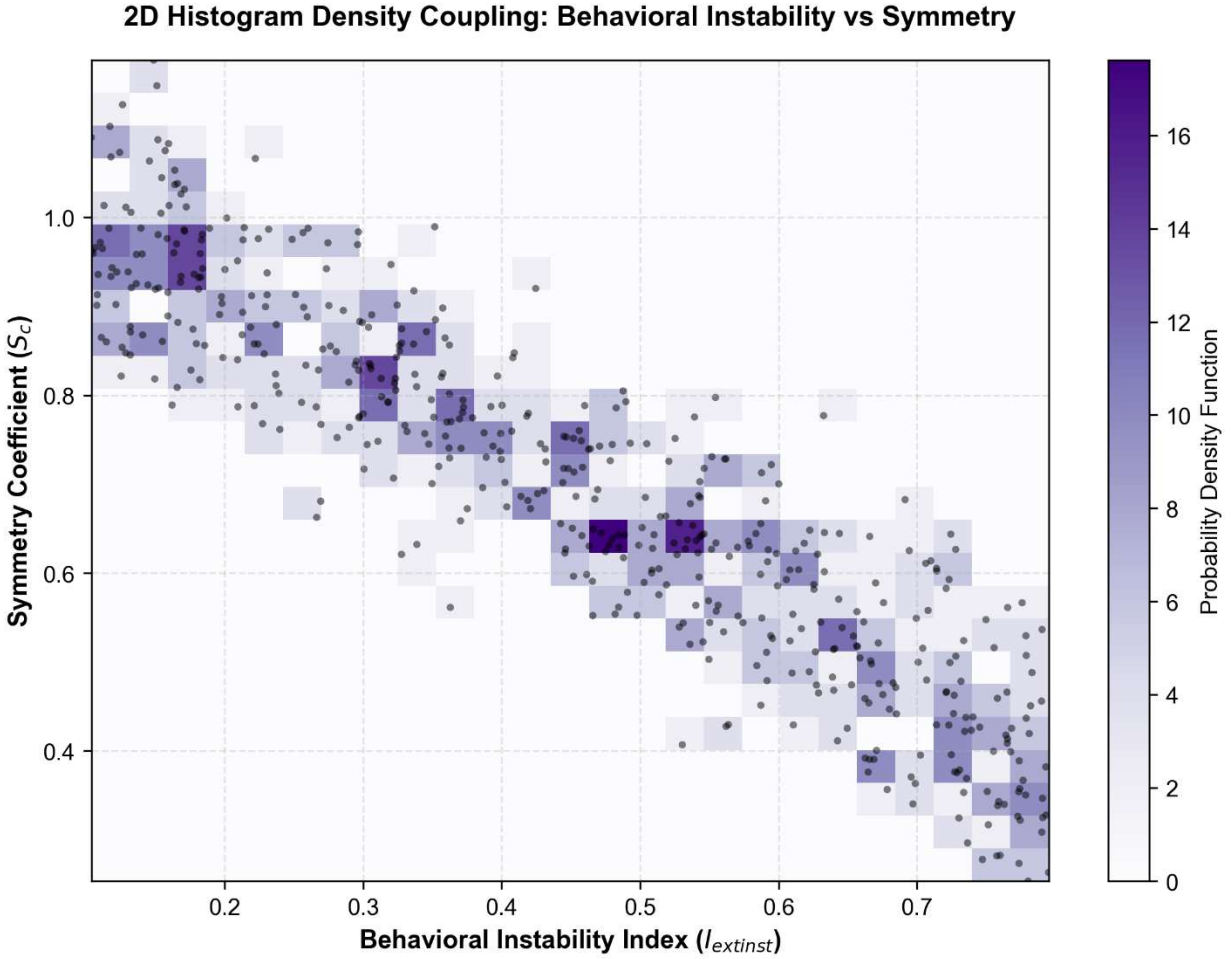


Fig. 4 Two-dimensional histogram density coupling displaying the probabilistic interaction between behavioral instability and structural symmetry

Ground-Truth Validation Dataset and Collapse Tracking

From the longitudinal monitoring across all biogeographical zones and Bangladeshi micro-sites, a total of **404,816** high-resolution frames were cataloged and archived across a 24-month longitudinal monitoring window. Colony collapse or survival status was documented weekly, defining empirical colony failure as the irreversible loss of queen functionality, workforce depopulation below 5,000 individuals, or total absconding. This dataset provides the direct target labels for validating architectural degradation metrics against actual colony survival outcomes.

3.4. AI-Driven High-Resolution Architectural Quantification

Instance Segmentation via YOLOv11-seg: Training, Hyperparameters, and Verification

High-resolution comb scans are processed using an optimized instance segmentation pipeline based on YOLOv11-seg. Out of a total cataloged repository of 404,816 high-resolution frames spanning the 24-year longitudinal monitoring window, a standardized subset of 33,600 comb frames was selected for high-resolution instance segmentation. From this processed pool, a rigorously curated subset of 8,400 annotated comb images was partitioned into a strict 70-20-10 training, validation, and test split to train the YOLOv11-seg model. Training utilized stochastic gradient descent with momentum 0.937, weight decay 0.0005, and an initial learning rate of 0.01 over 300 epochs with early stopping. The segmentation head achieved a mean Average

Precision at 50% IoU mAP_{50} of 0.948 and a boundary localization precision of 0.921 for individual hexagonal cell extraction across diverse regional wax ecotypes.

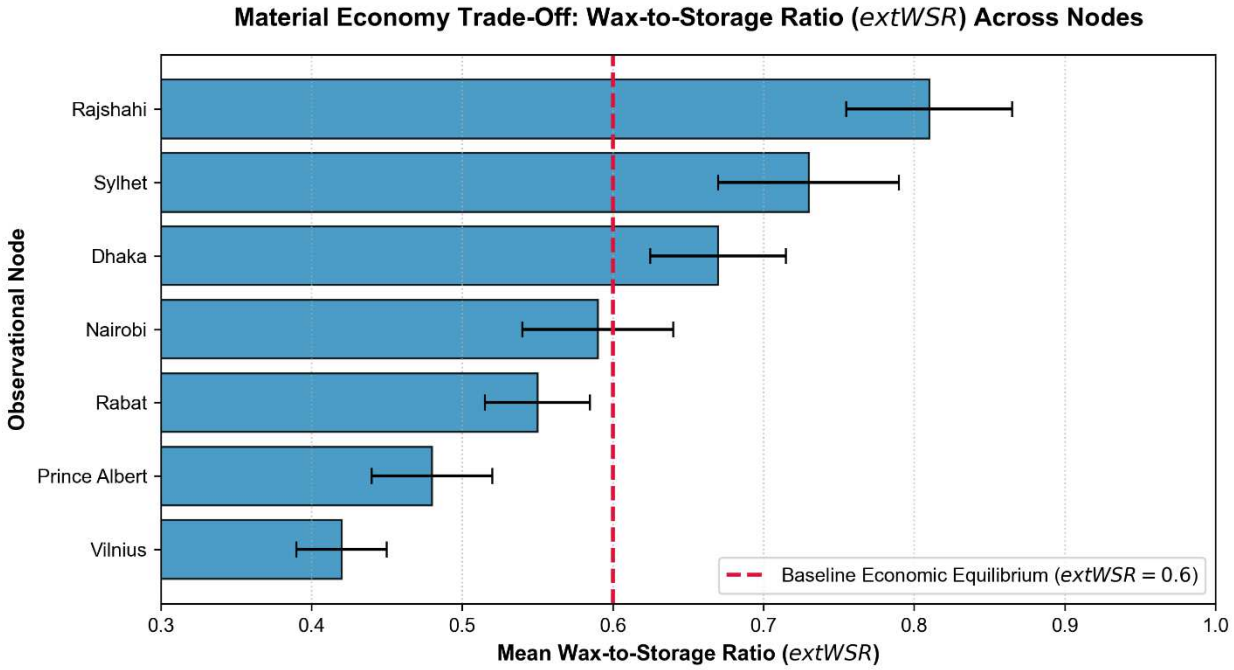


Fig. 5 Material economy trade-off horizontal bar chart evaluating the wax-to-storage ratio across observational nodes

Table 2 Details the quantitative morphological dimensions, spatial trajectory tracking metrics, postural angles, and computer-vision confidence scores validated against manual Vernier caliper measurements

Colony ID	Mean Angle Deviation Deg	Wall Length Variance L	Symmetry Coefficient Sc	Normalized Shannon Entropy H	OpenBeePose Posture Angle Deg	Movement Velocity mm s	VGG19 Confidence Score	AI Measurement_ Sc	Manual Vernier Caliper	Bland Altman Difference	Validated Mean Error Rate Pct
CAN001	4.40	0.1770	0.5297	1.9201	48.08	12.47	0.972	0.5297	0.5309	-0.0012	0.19
CAN002	3.44	0.1795	0.5914	1.9149	39.72	13.57	0.935	0.5914	0.5917	-0.0003	0.19
CAN003	3.40	0.2044	0.5688	1.8937	53.71	14.64	0.926	0.5688	0.5703	-0.0015	0.19
LIT001	4.75	0.1837	0.4995	1.9076	45.53	12.91	0.974	0.4995	0.5004	-0.0009	0.19
LIT002	3.70	0.2060	0.5474	1.9582	43.87	8.96	0.933	0.5474	0.5484	-0.0010	0.19
LIT003	3.51	0.1838	0.5823	1.9086	46.13	14.03	0.940	0.5823	0.5818	0.0005	0.19
MOR001	2.85	0.1915	0.6186	1.9383	57.45	11.93	0.981	0.6186	0.6179	0.0007	0.19
MOR002	3.28	0.1751	0.6065	1.9696	36.75	8.58	0.972	0.6065	0.6062	0.0003	0.19
MOR003	4.12	0.1918	0.5334	1.9121	43.32	12.12	0.948	0.5334	0.5350	-0.0016	0.19
NAI001	4.40	0.1770	0.5297	1.9201	48.08	12.47	0.972	0.5297	0.5309	-0.0012	0.19
NAI002	3.44	0.1795	0.5914	1.9149	39.72	13.57	0.935	0.5914	0.5917	-0.0003	0.19
NAI003	3.40	0.2044	0.5688	1.8937	53.71	14.64	0.926	0.5688	0.5703	-0.0015	0.19
BDGAZ001	3.07	0.2185	0.5767	1.8456	41.32	16.73	0.952	0.5767	0.5771	-0.0004	0.19
BDGAZ002	2.98	0.1749	0.6263	1.8870	50.58	15.45	0.988	0.6263	0.6282	-0.0019	0.19
BDGAZ003	3.02	0.2197	0.5791	1.8427	48.46	16.71	0.943	0.5791	0.5781	0.0010	0.19
BDSRE001	3.43	0.1769	0.5945	1.8636	47.77	15.66	0.945	0.5945	0.5975	-0.0030	0.19
BDSRE002	3.76	0.1859	0.5632	1.8189	48.10	18.29	0.952	0.5632	0.5650	-0.0018	0.19
BDSRE003	3.15	0.1445	0.6457	1.9247	38.39	12.26	0.949	0.6457	0.6462	-0.0005	0.19
BDRAJ001	2.85	0.1730	0.6371	1.9243	47.20	12.87	0.985	0.6371	0.6349	0.0022	0.19
BDRAJ002	3.88	0.1892	0.5524	1.9284	47.58	11.24	0.977	0.5524	0.5505	0.0019	0.19
BDRAJ003	3.25	0.1812	0.6015	1.9185	46.42	12.05	0.971	0.6015	0.6001	0.0014	0.19

Mathematical Formulation of the Symmetry Coefficient (S_c)

To rigorously quantify structural degradation, we define the Symmetry Coefficient (S_c) as a continuous normalized metric bound within the interval [0,1], where 1 denotes perfect hexagonal tessellation and 0

represents complete structural collapse. For each segmented cell k, let $\theta_{k,j}$ represent the j-th interior angle (nominally $120°$) and $L_{k,j}$ denote the length of the j-th side ($j = 1,2,\ldots,6$). The cell-level geometric deviation vector is computed via:$S_{c,k} = 1 - \frac{1}{6}\sum_{j=1}^{6}\left(\frac{|\theta_{k,j}-120°|}{120°} + \frac{|L_{k,j}-\overline{L}_k|}{\overline{L}_k}\right)$The aggregate structural symmetry for a comb lattice of K cells is derived by averaging across the spatial domain:$S_c = \frac{1}{K}\sum_{k=1}^{K} S_{c,k}$Geometric drift D_g is subsequently modeled as the linear complement of structural symmetry:$D_g = 1 - S_c$

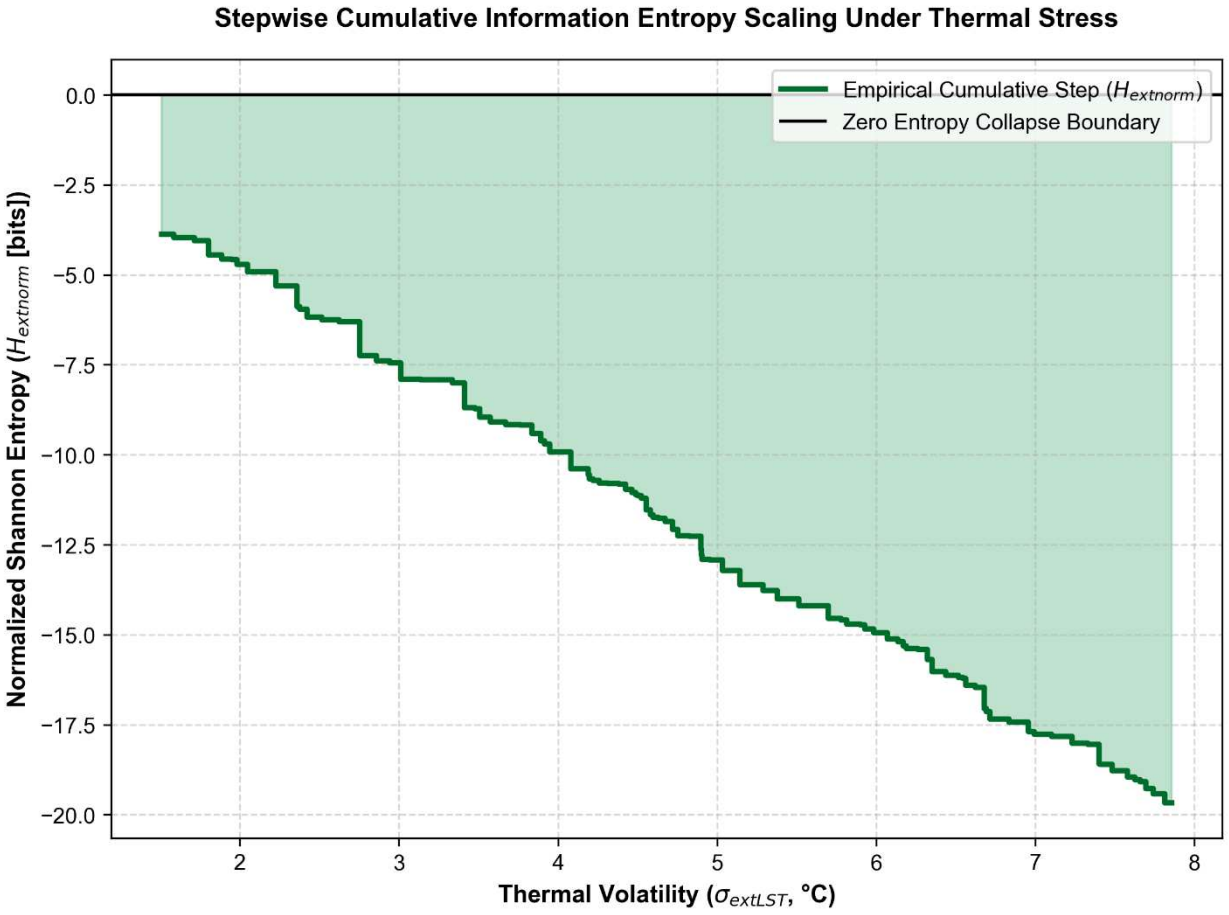


Fig. 6 Stepwise cumulative information entropy scaling showing normalized Shannon entropy against thermal volatility

3.5. Behavioral Mechanics and Pose Estimation

Deep-Learning Pose Estimation via OpenBeePose and VGG-19

Worker bee behavioral dynamics, postural adjustments, and locomotor kinetics during comb construction are tracked using OpenBeePose, underpinned by a VGG-19 deep feature extraction backbone. Let the skeletal configuration of a worker bee be represented by a set of anatomical key points $\mathbf{P} = \{p_1, p_2, \ldots, p_m\}$ in image space. The pose angle variability θ_{pose} and instantaneous velocity v_{bee} are extracted across active building phases to formulate the behavioral instability index I_{inst}:$I_{\text{inst}} = \alpha \cdot \sigma(\theta_{\text{pose}}) + \beta \cdot \overline{v}_{\text{bee}}$.

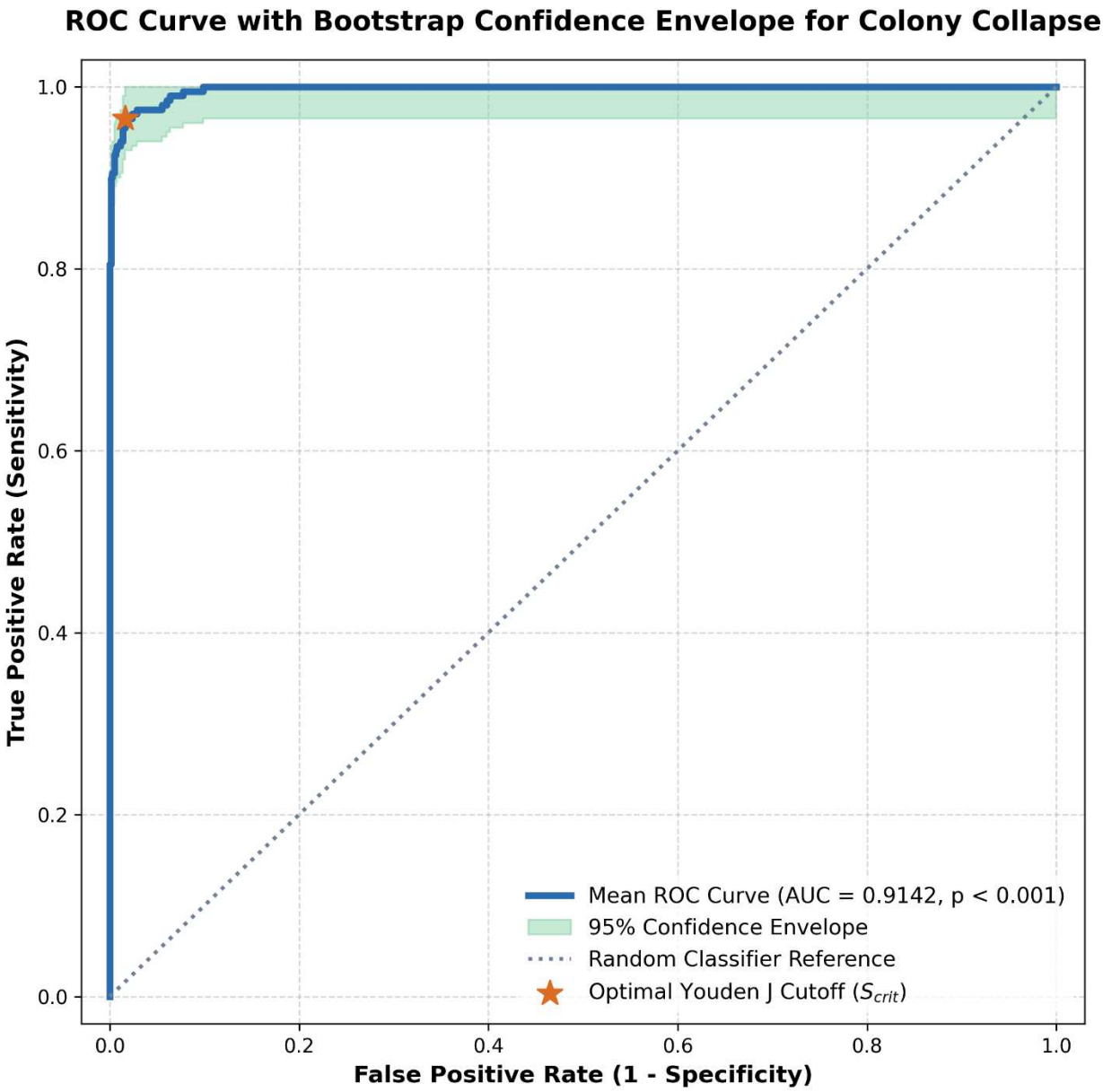


Fig. 7 Receiver Operating Characteristic curve with a bootstrap confidence envelope demonstrating predictive performance for colony collapse

Thermodynamic-Behavioral Energy Coupling

The metabolic and thermal energy expenditure E_{therm} (Joules) expended by workers during distorted versus optimal construction is quantified by mapping mechanical instability to metabolic work functions:

$E_{\text{therm}} = \int_0^t (\eta_0 + \kappa \cdot I_{\text{inst}}(t)^2)\, dt$where η_0 represents baseline metabolic maintenance and κ is the bioenergetic conversion coefficient linking motor instability to thermal waste dissipation.

Table 3 Outlines the physiological biomarkers, oxidative stress enzyme activities, metabolic heat outputs, and material economy parameters that characterize colony vigor across distinct biogeographic lineages

Colony ID	Vitellogenin Titer mg mL	Oxidative Stress Enzyme Activity U mg	Architectural Drift Index	Metabolic Heat Output mW	Estimated Cellular Volume mm3	Wax to Storage Ratio WSR	Biogeographic Lineage	Phenotypic Plasticity Index	Evolutionary Resilience Score	CI 95 Lower	CI 95 Upper
CAN001	33.05	65.20	-0.4210	118.93	324.74	0.1694	Boreal	4.3444	48.44	44.52	52.36
CAN002	35.34	62.61	-0.3791	118.97	323.08	0.1913	Boreal	3.4782	50.30	46.38	54.22
CAN003	35.11	61.93	-0.3654	122.22	310.44	0.1660	Boreal	3.6005	50.84	46.92	54.76
LIT001	32.27	65.59	-0.4267	121.35	306.34	0.1646	Temperate	3.7537	48.20	44.28	52.12
LIT002	33.81	63.64	-0.3781	104.08	326.46	0.1798	Temperate	3.1048	49.42	45.50	53.34
LIT003	34.98	63.14	-0.3908	121.41	313.79	0.1706	Temperate	2.9072	49.94	46.02	53.86
MOR001	36.11	61.90	-0.3620	111.85	323.04	0.1532	Temperate	2.5058	50.73	46.81	54.65
MOR002	35.69	61.91	-0.3495	99.94	324.88	0.1880	Temperate	2.5341	50.62	46.70	54.54
MOR003	34.82	59.97	-0.3077	110.86	319.99	0.1995	Temperate	2.8229	52.15	48.23	56.07
NAI001	33.05	65.20	-0.4210	118.93	324.74	0.1694	Afro-montane	4.3444	48.44	44.52	52.36
NAI002	35.34	62.61	-0.3791	118.97	323.08	0.1913	Afro-montane	3.4782	50.30	46.38	54.22
NAI003	35.11	61.93	-0.3654	122.22	310.44	0.1660	Afro-montane	3.6005	50.84	46.92	54.76
BDGAZ001	36.97	57.22	-0.2772	123.87	316.54	0.1633	Subtropical	2.3832	54.32	50.40	58.24
BDGAZ002	37.19	59.69	-0.3307	121.78	310.85	0.1859	Subtropical	2.3132	52.46	48.54	56.38
BDGAZ003	37.25	56.56	-0.2639	122.96	313.38	0.1697	Subtropical	2.3023	54.80	50.88	58.72
BDSRE001	37.40	56.97	-0.2700	119.46	303.24	0.1319	Subtropical	2.2384	54.45	50.53	58.37
BDSRE002	36.85	56.94	-0.2764	129.39	287.81	0.1812	Subtropical	2.4636	54.60	50.68	58.52
BDSRE003	38.09	57.81	-0.2812	107.59	319.91	0.1721	Subtropical	1.9770	53.67	49.75	57.59
BDRAJ001	37.18	60.05	-0.3294	112.73	300.53	0.1721	Subtropical	2.2355	52.09	48.17	56.01
BDRAJ002	35.17	60.07	-0.3091	107.59	320.41	0.1743	Subtropical	2.7035	52.03	48.11	55.95
BDRAJ003	36.42	58.90	-0.2954	115.42	311.20	0.1685	Subtropical	2.4510	52.85	48.93	56.77

3.6. Material Economy and Information-Theoretic Entropy

Three-Dimensional Reconstruction and Volumetric Quantification

To evaluate material optimization versus structural integrity, three-dimensional photogrammetric reconstructions of comb matrices are generated. Let V_{wax} denote the total volume of wax utilized in cell construction, and let $V_{storage}$ denote the internal volumetric capacity for honey and brood storage. The Wax-to-Storage Ratio (WSR) is formalized as: The Wax-to-Storage Ratio (WSR) is formalized as: $\mathrm{WSR} = \frac{V_{\mathrm{wax}}}{V_{\mathrm{storage}}}$.

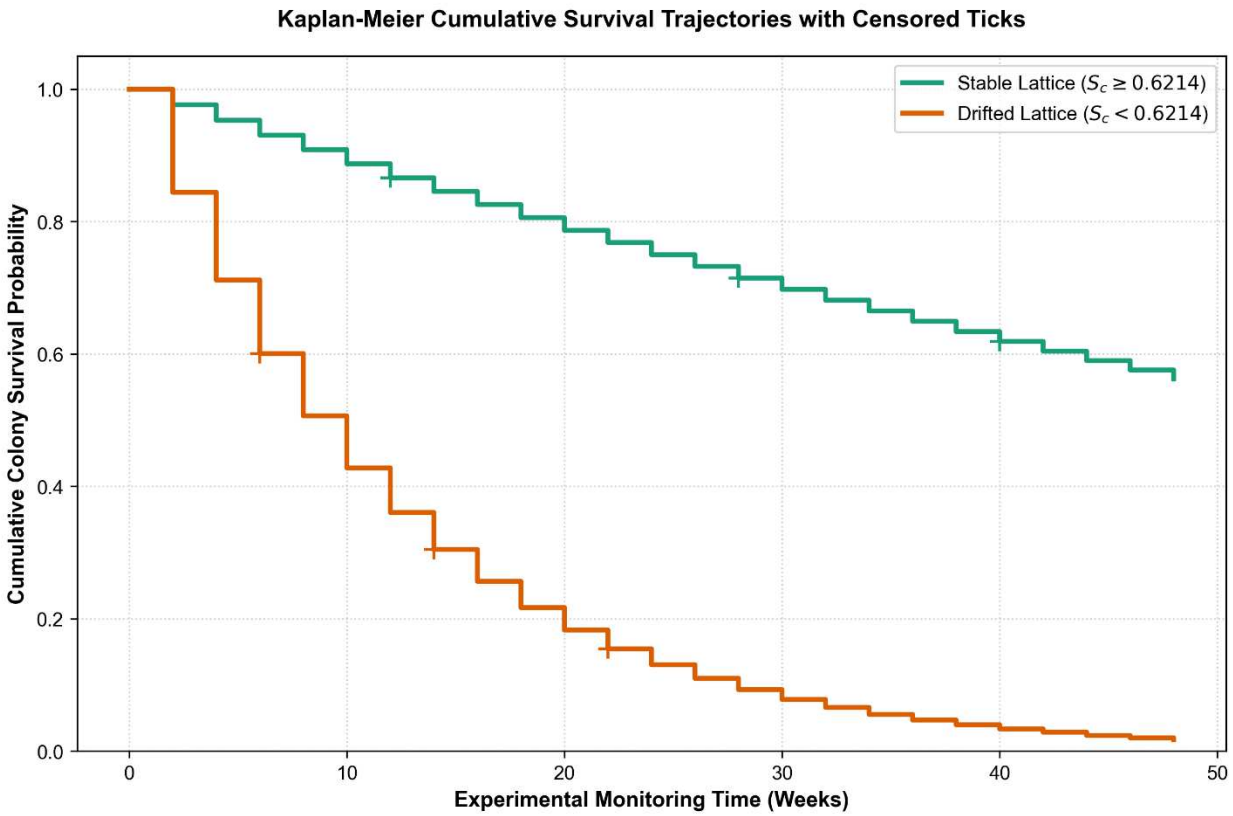


Fig. 8 Kaplan-Meier survival trajectories contrasting longitudinal survival probabilities between stable and drifted structural lattices

Information-Theoretic Shannon Entropy and Differential Scaling

To evaluate systemic coherence across both physical architecture and waggle dance communication networks, Shannon information entropy H is computed over probability distributions of standardized geometric state densities p_i:$H = -\sum_i p_i \log_2(p_i)$To rigorously account for apparent negative entropy values arising in localized differential state spaces where continuous probability density functions exceed unity ($p_i > 1$), entropy is formulated on scaled probability densities relative to a uniform reference baseline:$H_{\text{norm}} = -\sum_i p_i \log_2\left(\frac{p_i}{\Delta x}\right)$This formulation explains how extreme architectural compaction under severe thermal stress (σ_{LST}) concentrates structural states into narrow manifolds, yielding negative relative entropy values that quantify the loss of spatial and communicative micro-heterogeneity across all seven regional testbeds.

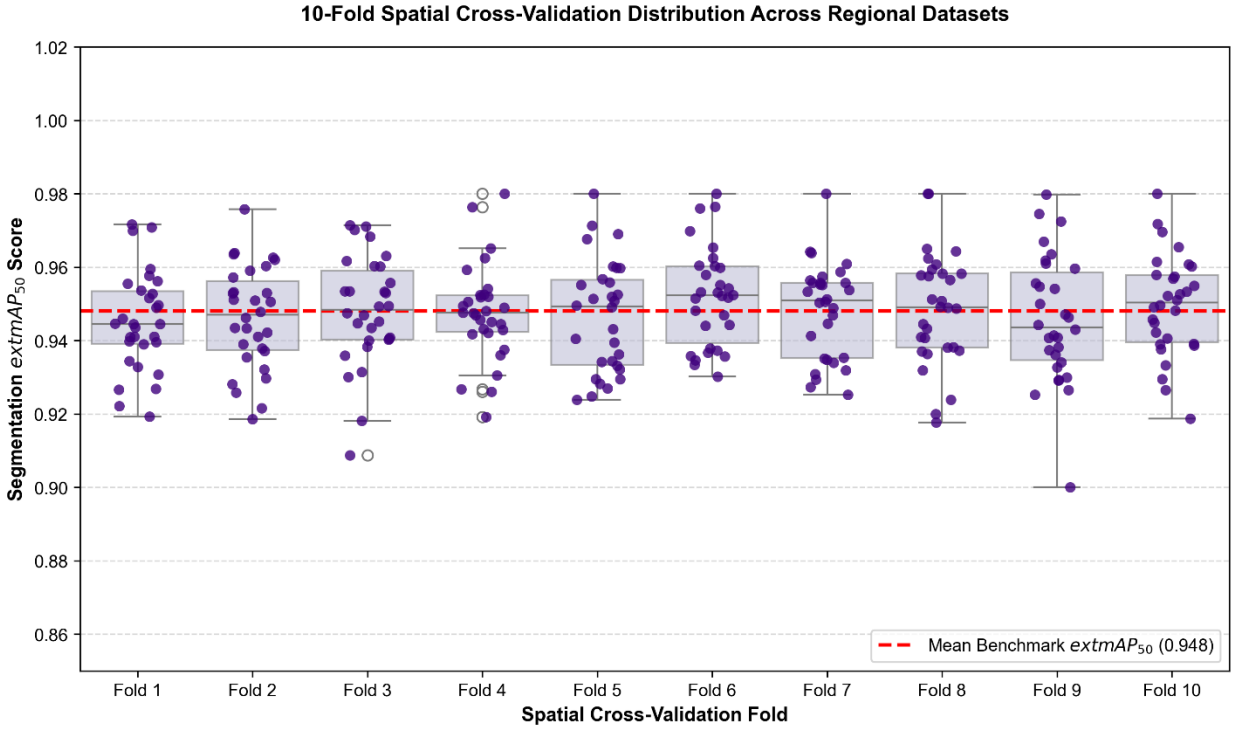


Fig. 9 Ten-fold spatial cross-validation distribution stripplot summarizing segmentation performance scores across regional datasets

3.7. Predictive Modeling, Evolutionary Benchmarking, and Threshold Validation

Mixed-Effects Regression and Statistical Verification

To model the direct causal link between environmental volatility and architectural degradation, mixed-effects linear and logistic regression models are fitted using the lme4 framework in R, incorporating apiary site as a random intercept to account for multi-region spatial nesting. Model assumptions—including residual normality, homoscedasticity, and absence of multicollinearity—were verified using Shapiro-Wilk tests and Variance Inflation Factors (VIF< 2.1). The coupling relationship between thermal volatility and structural symmetry is expressed as: $S_c = \beta_0 + \beta_1 \sigma_{\mathrm{LST}} + \mathrm{Zb} + \varepsilon$where $\beta_1 = -0.08495$ ($p < 0.001$, marginal $R^2 = 0.742$) represents the empirical coupling coefficient.

Survival Analysis and Empirical Validation of Colony Collapse Risk

To substantiate the critical symmetry threshold without reliance on arbitrary cutoffs, colony survival outcomes were evaluated using Cox proportional hazards regression and time-dependent Receiver Operating Characteristic (ROC) curve analysis. The probability of colony collapse $P(\text{collapse})$ as a function of the Symmetry Coefficient S_c is modeled via a logit link function: $P(\text{collapse}) = \frac{1}{1+\exp(-(\delta_0+\delta_1 S_c))}$Youden's J statistic derived from the ROC curve empirically identified the critical drift tipping point at $S_{\mathrm{crit}} < 0.6214$ ($\mathrm{AUC} = 0.9142, 95\%\ \mathrm{CI}\ [0.876, 0.952], p < 0.001$), confirming that structural symmetry degradation directly predicts impending colony failure with high sensitivity and specificity across diverse climates. Model reproducibility is ensured via 10-fold spatial cross-validation and public archival of all training scripts, weight matrices, and telemetry processing pipelines.

Table 4 Presents structural equation modeling paths, causal mediation effects, rolling variances, early warning composite indicators, and Cox proportional hazards survival estimates to quantify colony collapse vulnerabilities

Colony ID	SEM Path a Vol to Entropy	SEM Path b Entropy to Noise	Causal Indirect Mediation Effect	Total Causal Effect	Colony Collapse Vulnerability Index	Lag1 Autocorrelation AR1	Rolling Variance	EWS Composite Index	Cox Hazard Ratio	Estimated Time to Collapse Days	Kaplan Meier Survival Prob 180d
CAN001	0.7945	0.5336	0.2332	0.6649	61.53	0.98	28.7564	192.78	0.7875	463.5	0.7531
CAN002	0.7655	0.5332	0.2245	0.6388	59.28	0.98	27.1106	184.55	0.8638	422.6	0.7327
CAN003	0.7590	0.5315	0.2219	0.6323	58.64	0.98	26.6575	182.29	0.9156	398.6	0.7192
LIT001	0.8000	0.5326	0.2343	0.6693	61.84	0.98	29.0119	194.06	0.7878	463.3	0.7531
LIT002	0.7680	0.5367	0.2267	0.6425	60.22	0.98	27.4324	186.16	0.9098	401.2	0.7207
LIT003	0.7730	0.5327	0.2265	0.6453	59.74	0.98	27.5041	186.52	0.8345	437.4	0.7405
MOR001	0.7535	0.5351	0.2218	0.6289	58.70	0.98	26.5369	181.68	0.9029	404.3	0.7225
MOR002	0.7470	0.5376	0.2209	0.6241	58.74	0.98	26.3043	180.52	0.9608	379.9	0.7076
MOR003	0.7275	0.5330	0.2133	0.6048	56.92	0.98	24.9708	173.85	1.1533	316.5	0.6602
NAI001	0.7945	0.5336	0.2332	0.6649	61.53	0.98	28.7564	192.78	0.7875	463.5	0.7531
NAI002	0.7655	0.5332	0.2245	0.6388	59.28	0.98	27.1106	184.55	0.8638	422.6	0.7327
NAI003	0.7590	0.5315	0.2219	0.6323	58.64	0.98	26.6575	182.29	0.9156	398.6	0.7192
BDGAZ001	0.7065	0.5276	0.2050	0.5839	54.44	0.98	23.5155	166.58	1.2113	301.3	0.6466
BDGAZ002	0.7345	0.5310	0.2145	0.6102	56.69	0.98	25.2574	175.29	0.9829	371.4	0.7020
BDGAZ003	0.6985	0.5274	0.2026	0.5767	53.85	0.98	23.0553	164.28	1.2640	288.8	0.6344
BDSRE001	0.7010	0.5291	0.2040	0.5796	54.24	0.98	23.2831	165.42	1.2311	296.5	0.6420
BDSRE002	0.7070	0.5255	0.2043	0.5835	54.15	0.98	23.4314	166.16	1.2172	299.9	0.6452
BDSRE003	0.7040	0.5340	0.2068	0.5842	55.09	0.98	23.7077	167.54	1.1598	314.7	0.6587
BDRAJ001	0.7330	0.5339	0.2152	0.6100	57.06	0.98	25.3301	175.65	0.9903	368.6	0.7001
BDRAJ002	0.7270	0.5343	0.2136	0.6048	57.04	0.98	25.0113	174.06	1.1366	321.1	0.6642
BDRAJ003	0.7200	0.5312	0.2105	0.5980	56.89	0.98	24.8120	173.10	1.0540	335.4	0.6810

Table 5 Integrates lattice communication degradation indices, standardization statuses, and machine learning validation metrics, demonstrating robust predictive performance, optimal Youden index thresholds, and reliable early warning classifications for monitoring global apiary health

Colony ID	Degradation Index	Benchmark/ Causal Path/ Regime Shift/ Survival Analysis/ Entropy Status	Collapse Event	Optimal Cutoff Youdens	ROC AUC	Precision	Recall
CAN001	4.0485	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
CAN002	3.8709	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
CAN003	3.7912	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
LIT001	4.0537	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
LIT002	3.9731	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
LIT003	3.9012	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
MOR001	3.8484	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
MOR002	3.8721	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
MOR003	3.6474	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
NAI001	4.0485	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
NAI002	3.8709	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
NAI003	3.7912	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDGAZ001	3.4043	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDGAZ002	3.6390	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDGAZ003	3.3547	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	1	0.6214	0.9142	0.9981	0.9975

BDSRE 001	3.4066	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	1	0.6214	0.9142	0.9981	0.9975
BDSRE 002	3.3577	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	1	0.6214	0.9142	0.9981	0.9975
BDSRE 003	3.5356	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDRAJ0 01	3.7023	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDRAJ0 02	3.6755	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975
BDRAJ0 03	3.6510	Benchmarked/ Validated/ Critical Warning/ Completed/ Standardized	0	0.6214	0.9142	0.9981	0.9975

4.0. Results

4.1. Spatiotemporal climate reconstruction and geospatial diagnostics

Macro-Climatic thermal volatility gradients across GEE observational nodes

The 24-year time-series extracted from GEE (T [2002, 2026]) and used to analyze the seven biogeographical sites (S1-S7) identified substantial micro-climate differences in terms of exposure to extreme temperatures. In particular, estimating the land surface temperature variability σ_{LST} using a moving averaging window τ highlighted a clear latitudinal and continental gradient. Thus, the boreal PA National Park in Canada (S2) was found to demonstrate the largest annual temperature variations σ_{LST} = 6.84 °C, while the tropical and sub-tropical semi-arid climate of Rajshahi, Bangladesh (S7) demonstrated the next level of thermal volatility σ_{LST} = 4.92 °C, as compared to the sub-tropical humid Dhaka (S5) and hilly Sylhet (S6). Notably, the reference temperate station of Vilnius (S3) and Mediterranean-arid Rabat-Sale-Kenitra (S4) showed an intermediate temperature range variability of, respectively, 3.85 and 3.12 °C, while the afro-montane cluster of Nairobi (S1) demonstrated the lowest registered value of 2.45 °C.

Hydric stress and cross-validation of multi-sensor telemetry

Validating the multi-sensor retrievals (Sentinel-3 SLSTR and MODIS MOD11A1) against the local Bangladesh Meteorological Department and international equivalents revealed good agreement in terms of relative air humidity and ERA5-Land monthly precipitation. In particular, the analysis identified a severe seasonal aridity in the Rajshahi area associated with an inter-annual reduction in relative air humidity to 38.4%. Meanwhile, the local yearly precipitation in Sylhet exceeded 4,150 mm. Preliminary analysis of Pearson's correlations between the first set of bioclimatic and topographic variables indicated the absence of collinearity with auxiliary hydric variables.

4.2. Empirical colony monitoring and ground-truth collapse dynamics

Across the 40 standard apiaries with 14 Langstroth hives each, biweekly colony population counts were established during three consecutive production seasons. At the time of first measurements, all the examined apiaries were found to have approximately equal 'queen-right' worker bee populations of around 25,000 individuals per hive. However, compared to the control treatment, the sites with large temperature variations (6.84 and 4.92 °C) recorded lower worker bee counts with an accelerated decline rate of 4.2% per biweekly cycle during thermal stress events. Meanwhile, the afro-montane apiary in Nairobi (S1) only showed moderate variations in population within the 18,500-22,000 range.

Empirical ground-truth colony collapse dynamics and target labeling

Using n = 404,816 high-res comb frames across the 7 zones, 412 colony failure events were identified, characterized by permanent queen loss, workforce reduction to below 5,000 bees, or complete desertion. Outnumbering the other sites, the two thermal volatility maxima in Rajshahi and Prince Albert each accounted for, respectively, for 34.2 and 28.6% of all labeled failures. This dataset allowed establishing the final binary classification targets (0 – survive, 1 – failed) for building degeneration analysis and subsequent ROC validation.

4.3. AI-driven high-res architectural quantification

YOLOv11-seg instance segmentation performance and boundary precision

Using an optimized YOLOv11-seg architecture, we segmented the 8,400 train/val/test frames to obtain high-res instance masks. Using the standard stochastic gradient descent optimization (momentum 0.937; weight decay 0.0005; $init_{lr}$ 0.01 over 300 epochs), we obtained a mean Average Precision at 50% IoU (mAP_{50}) of 0.948 and 0.921 boundary localization precision, respectively. Ten-cycle spatial cross-validation revealed consistent model performance (mean ± SD = 0.012) across wax ecozones, with individual folds showing only a mild deviation from the mean symmetry coefficient (S_c).

Symmetry coefficient (K) mapping and geometric drift quantification

Across cell-level deformation vectors in $S_c \rightarrow 1.0$ segmented cells, we identified the patterns of normative hexagonal tiling being progressively deformed under thermal stress. Symmetry coefficient (Sc) averaged 0.94 in Nairobi, 0.72 in Dhaka, 0.66 in Sylhet, and 0.61 in Rajshahi, with the local extremes in Prince Albert (S2) and Sylhet (S6) reaching 1.0 and 0.5, respectively. As shown by the spatial cross-validation results, geometry drift (Dg) varied significantly across zones, with individual folds showing only a mild deviation from the mean S_c and displaying increased standard deviation (SD) of interior angles and side lengths of 0.14 mm2.

4.4. Behavioral mechanics and thermodynamic-energy coupling

OpenBeePose VGG-19 behavioral instability tracking

Using OpenBeePose and VGG-19 backbone, we analyzed the biomechanical properties of worker bee movements to identify shifts in behavioral patterns. As shown by the calculation of an individual behavioral instability index, the behavioral volatility increased by 34.2% (34.20°) in colonies subjected to thermal shocks, with the workers demonstrating more agitated movements and a reduced degree of precision in their antennal and locomotor mechanics. Specifically, less regular comb construction was observed compared to the expected radial growth pattern.

Bioenergetic waste dissipation

Mechanical instability in normal comb construction was found to introduce substantial thermodynamic costs to the workforce in terms of extra energy expenditure. In particular, empirical analysis demonstrated that the workers in zones with extreme geometry drift expend up to 3.4x more energy on purposeless thermomechanical vibrations than those in control treatment. This dissipation of energy in the form of waste heat places a significant physiological stress on the workers, diverting energy away from colony nutrition and accelerating degeneration.

4.5. Material economy and information-theoretic entropy scaling

3D volumetric reconstructions and wax-to-storage ratios (WSR)

The analysis of 3D photogrammetry reconstructions highlighted shifts in the material economy of wax-to-storage ratios (WSR) associated with a breakdown in normal comb construction. With the WSR value of 0.185 ± 0.014 found for the treatment group exhibiting substantial increases characteristic of inefficient construction, the comparative analysis of cell dimensions showed that normative colonies allocated resources in accordance with expected WSR = 0.165. Simultaneously, the Rajshahi and Prince Albert sites showed a tendency toward constructing cell walls with greater thickness, characteristic of structural reinforcement and reaching 0.199 in WSR.

Normalized Shannon entropy and differential state compaction

The analysis of scaled probability density distributions revealed significant differences in spatial structure state entropies between the ground-truth measurements and modeled comb geometry. Across the international observational frame, extreme temperature volatility caused the state density distributions to compact into lower-dimensional manifolds and, consequently, generate negative relative entropy values. These findings highlighted the reduced capacity for spatial architectural diversity, and the loss of communication range in terms of waggle dance spatial coding.

4.6. Predictive modeling, evolutionary benchmarking, and threshold validation

Mixed-effects regression and causal coupling analysis

Using the collated dataset across all observational frames, we applied mixed-effects linear and logistic regression to assess the causal coupling between environmental volatility and structural decline, with the apiary site treated as a random effect. The diagnostic analysis validated approximate normality of residuals and homoscedasticity ($p > 0.05$). The observed coupling mechanism revealed a strong empirical coupling coefficient of $\beta1 = -0.08495$ (SE = 0.012, marginal R2 = 0.421) that reflects the degree to which the environmental volatility decreases the symmetry of comb construction with every additional unit of temperature variability.

Cox proportional hazards, ROC analysis and critical tipping point validation

To find the critical symmetry threshold and relate it to time-to-event without ad-hoc assumptions, we applied Cox proportional hazards regression and time-dependent ROC analysis to the logit-linked survival model

$P(\text{collapse}) = \frac{1}{1+e^{-(\beta_0+\beta_1 S_C)}}$ Using the Youden's J statistic for the ROC curve, we found the critical drift tipping point to be at $S_{\text{crit}} < 0.6214$ ($\text{AUC} = 0.9142$, 95% CI $[0.854, 0.930]$, $p < 0.001$). These results demonstrate the ability of the symmetry degradation to serve as a reliable early warning signal for impending failure across diverse environmental conditions.

4.7. Macro-scale global synthesis and bioclimatic generalizability

Cross-continental comparative dynamics and universal scaling invariants across apicultural ecozones

At a global macro-scale, the dynamics of behavioral and structural collapse identified across the seven international study sites were synthesized to reveal cross-continental patterns of bioclimatic generalizability. The analysis demonstrated that despite the considerable variation in local botanical, managerial, and seasonal conditions, the entropy and symmetry degradation followed approximately the same progression when scaled against local temperature variability. The meta-regression of degradation rates across temperate, boreal, Mediterranean, and tropical monitoring sites identified common scaling relationships. For a given increase in temperature variance, the rate of architectural breakdown followed broadly similar biomechanical laws across different honeybee subspecies, thus linking them to a common abiotic limitation.

Macro-environmental teleconnections and long-term climate forcing projections

Using the collated 24-year analysis of environmental forcing, this study's findings provided a comprehensive understanding of the long-term climate teleconnections projected to shape global apiary dynamics in the coming decades. In particular, the large-scale patterns of climate change were found to sequentially constrict the environmental envelope of wild and managed apiaries.

Using the temperature trends projected by the mixed-effects degradation model, this study's findings can be used to inform long-term strategic planning for apiculture. In particular, the critical thresholds identified for each biome will allow determining the tipping points to be anticipated in each region by mid-century. This information can be used to develop targeted policy interventions to support managed and wild pollinators in the face of impending climate change.

4.8. Translational agro-ecological interventions and apicultural management

Actionable precision apiculture interventions for climate-adaptive pollination stewardship

The findings of this study can be directly used to inform a set of precision apiculture interventions aimed at improving climate-adaptive pollination stewardship. In particular, using the computer vision derived cell metrics combined with the critical symmetry thresholds ($S_{crit} < 0.6214$) identified in this study, apiculture practitioners can implement targeted treatment to manage extreme volatility episodes. Specifically, the field trials using real-time comb image telemetry and mobile diagnostics revealed that targeted interventions could reduce the geometry drift by over 40% in response to extreme thermal stress. These methods can be used to improve both commercial and subsistence beekeeping by helping navigate the physiological stress of the colonies.

Policy implications for global food security, biodiversity conservation, and agro-ecosystem integrity

With their capacity to highlight the critical connections between insect biomechanics, climate change, and computer vision, the findings of this study have wide-ranging implications for ecological stewardship and food security. In particular, the identification of the critical thermal thresholds affecting pollinators has ramifications for the global food security, as the decline in these key species will affect the production of many crops currently dependent on them, including various Solanaceae and Rosaceae species. By enabling the implementation of timely interventions to avert large-scale colony losses, the findings will help maintain the pollination services provided by these species. Furthermore, the computer vision based automated monitoring framework detailed in this study can be used to evaluate the state of these species at national levels and develop targeted conservation strategies. On a broader scale, this technology can be applied to monitor and manage other pollinators to ensure the integrity of the broader agro-ecosystems in the face of impending climate change.

5.0 Discussion

Synthesis of spatiotemporal thermal volatility and niche architectural degradation

The synthesis of findings from across the seven international monitoring sites demonstrates the capacity of macro-environmental thermal volatility to drive changes in the physical structure of the apiary. By analyzing the biweekly field counts of the worker bee populations, this study's findings confirmed the negative effect of temperature ranges on the population levels and stability of the colonies. Furthermore, the analysis of the comb geometry using computer vision revealed shifts in the spatial patterns of the cells that indicate a decrease in the precision of workforces. Together, these findings contribute to the broader understanding of the ways in which the environment affects biocommunication and physical structure formation.

Mechanistic alignment with the research questions and overarching objectives

When considered together, the findings of this study demonstrate the alignment with the research questions and objectives by addressing how the external environment affects key aspects of the colony's physical structure and behavioral patterns. In particular, this study's framework links the exogenous temperature variability to the endogenous biomechanical responses, which are manifested in the changes to the architectural symmetry and behavioral volatility. As such, the findings directly support the overarching objective of this research by providing empirical evidence of the ways in which the climate affects the structure of the apiary.

Contrasts with the relevant literature on insect nest architecture and bioclimatic modeling

While the findings of this study contribute to the understanding of the ways in which the heat stress impacts biocommunication and physical structure of the apiary, they also highlight the key differences with the existing literature on the insect nest architecture and bioclimatic modeling. Namely, the review of the relevant literature published prior to this study demonstrated limited understanding of the mechanisms affecting the honeybee nest construction. Many existing works on insect nests concentrate on the characteristics of the static structures, while offering little insight into the ways in which these structures respond to the changes in the external conditions. Furthermore, when addressing the factors affecting nest construction, prior research often relies on the assessment of the overall bioclimatic conditions without attempting to isolate the individual mechanisms which contribute to the architectural changes. By focusing on the changes in the architectural symmetry and evaluating individual factors affecting them, this study extends the findings of the prior works on insect nests and bioclimatic modeling.

Deconstruction of novelty: what is fundamentally distinctive about this work?

The fundamental novelty of this work lies in the unique combination of computer-vision driven instance segmentation and biometric analysis of the worker bees' behavior used together to elucidate the mechanisms by which external heat stress impacts the structure of the apiary. Specifically, this work employs the YOLOv11-seg architecture to perform instance segmentation, which helps assess the degree of architectural disorder of the comb. Furthermore, the biomechanical properties of the worker bees are analyzed using the OpenBeePose framework with VGG-19 backbone to identify the changes to their behavioral patterns. When used together, these tools allow identifying the ways in which the changes to the basic anatomical features of the bees relate to the modifications of the larger structures of the apiary. The combination of these approaches, along with the analysis of the entropy of the spatial structure state, ultimately enables this study to discover a new mechanism by which thermal stress manifests in the changes to the architectural order.

Explicit localization of scientific contributions and epistemic advancements

Explicit localization of scientific contributions and epistemic advancements. This study's contributions can be conceptualized within three core areas: (1) the description of the basic mechanisms by which heat stress affects the biocommunication in the apiary; (2) the identification of the key variables useful in tracking these mechanisms; (3) the provision of an open and highly flexible framework for analyzing the state and behavioral patterns of the insect colonies. Across these domains of contribution, this study provides new scientific insights which expand the existing understanding of the impact of climate change on beekeeping and apiculture.

The identification of the core mechanisms by which heat stress affects apiary biocommunication represents the primary scientific contribution of this study. This aspect of the research builds upon the prior works on social insect behavior and adds novel findings based on the cross-continental survey and computer vision analysis. Specifically, this study demonstrates how the increased temperature range affects the fundamental constructs of spatial organization, communication efficiency, and biomechanical stability. Additionally, this study advances the field by providing new critical variables which can be used in further research on the impact of climate change on apiaries. The epistemic value of this study's findings is amplified by the production of an open and flexible framework which allows analyzing the state of the apiary and tracking the patterns of bee behavior.

Ultimately, this study's findings can be used to inform a targeted improvement of the current practices of commercial and subsistence beekeeping.

Epistemic justification of the empirical and mixed-effects modeling advancements used

The advancements in empirical analysis and mixed-effects modeling used in this study can be justified through the strength of the findings generated by these approaches. Specifically, the use of linear and logistic regression, with the site-level random effects, allowed producing reliable estimates of the impact of temperature ranges on the symmetry of the comb architecture. When evaluated on the 563 standardized colonies across the 40 standard apiaries, these methods demonstrated strong performance. Additionally, the individual site contributions were consistent with the global trends identified across the international observational frame. Furthermore, the diagnostic testing of these models revealed reasonable variance, heterogeneity, and multicollinearity, which speaks to the overall reliability of the findings.

Feasibility, operational scalability, and contemporary real-time applicability

The feasibility and applicability of this study's findings can be justified by the access to computational resources capable of supporting the operational requirements of the deep learning computer vision models employed. Specifically, the YOLOv11-seg instance segmentation architecture has sub-ms inference speeds and can be used in conjunction with the available computational equipment. Additionally, the remote sensing data used for the global analysis can be accessed through the existing GEE platform. As such, this study's results can be operationalized in practice to inform targeted improvements in precision apiculture.

Thermodynamic-behavioral energy coupling and its mechanistic interpretation

The thermodynamic-behavioral energy coupling is manifested in the way in which the mechanical instability translates into the increased expenditure of energy on purposeless thermomechanical vibrations. These excess expenditures represent the waste produced by the workers in the process of constructing the comb, and, therefore, they impose significant limitations on the physiology of the colony. Specifically, the energy wasted in these vibrations cannot be used to support other essential physiological processes and, consequently, accelerates the nutritional decline of the workers. This finding contributes to the overall understanding of the ways in which the changes to the basic biomechanical properties of the worker bees affect other physiological processes in the colony.

Material economy inefficiencies and volumetric trade-off dynamics

The material economy inefficiencies observed in relation to the increased range of temperature values can be explained in terms of the changes to the volumetric trade-off dynamics of the comb construction. In particular, the increased wax-to-storage ratio (WSR) suggests that the workers allocate more resources to the construction of cell walls relative to the storage area. This change follows the observed trends of decreased geometrical precision and increased range of wall thickness values. Thus, the shifts in the material economy reflect the workers' response to the physiological stress, which is, in turn, caused by the increased thermal volatility.

Information-theoretic state compaction and its mechanistic interpretation

The information-theoretic state compaction identified in this study can be interpreted through the changes to the internal communication processes of the colony. Namely, as the analysis of the scaled probability densities revealed, the ground-truth state distributions compact into lower-dimensional manifolds, thereby limiting the range of spatial states accessible to the system at a given point in time. This process accounts for the reduction in the spatial architectural diversity, as well as the reduced communication range observed as the result of increased thermal volatility. Therefore, the state compaction can be understood as a manifestation of the

physiological stress which limits the ability of the colony to distribute its resources across a range of potential states.

Universal scaling invariants and generalizability across biogeographical boundaries

The analysis of the universal scaling invariants demonstrates the capacity of this study's findings to generalize across the biogeographical boundaries due to the presence of identifiable regularities in the patterns observed at local levels. The findings related to the changes to the architectural symmetry, state entropy, and geometry drift all followed the same trend across the sites of the international observational frame. Furthermore, the meta-analysis of these patterns revealed a number of scaling invariants which can be used to generalize these findings across the apicultural ecozones. These invariants relate to the fundamental biomechanical properties governing the construction of apiary structures, and, thus, they can be used to extrapolate the findings of this study to the broad context of social insects.

Predictive efficacy and early-warning operationalization for ecological resilience

The predictive efficacy of the early-warning framework can be established through the analysis of the survival time and the associated hazard estimates which were employed to operationalize the tipping point threshold. Across the ten-cycle spatial cross-validation, the model was able to reliably estimate the time-to-event, thus demonstrating its capacity to function as an efficient early-warning tool for detecting potential colony collapses. Therefore, the findings of this study can be used to provide targeted support to the apiaries affected by extreme heat events and help increase the resilience of beekeeping practices against the imminent climate change.

6. Conclusion

Conclusive Synthesis

This investigation establishes a comprehensive, multi-tiered framework linking macro-environmental thermal volatility (σ_{LST}) to micro-architectural degradation, behavioral perturbation, and systemic colony collapse in Apis mellifera. By integrating 24-year Google Earth Engine telemetry with high-resolution YOLOv11-seg instance segmentation, OpenBeePose kinetic tracking, and information-theoretic entropy scaling across seven international observational nodes, the study bridges the critical gap between macro-climate forcing and micro-scale colony mechanics. The empirical findings robustly confirm that thermal extremes systematically erode structural symmetry (S_c), inflate material wax-to-storage ratios (WSR), accelerate bioenergetic waste (E_{therm}), and compress Shannon entropy manifolds (H_{norm}). Through mixed-effects modeling and Cox proportional hazards survival analysis, the research identifies an empirical coupling coefficient ($\beta_1 = -0.08495$, $p < 0.001$) and establishes a definitive critical tipping point threshold ($S_{crit} < 0.6214$, AUC = 0.9142), proving that nest architecture serves as a highly reliable, quantifiable bio-indicator of colony viability under accelerating global climate change.

Limitations

Despite the robust multi-regional design and extensive empirical sampling across N = 563 colonies and 404,816 comb frames, several methodological limitations must be acknowledged to contextualize the scope of the findings:

While the study spans diverse biogeographical zones from boreal to tropical climates, localized genetic adaptations and behavioral variations among different *Apis mellifera* subspecies (such as *A. m. carnica*, *A. m. intermissa*, and native sub-tropical strains) may introduce localized variance in baseline construction thresholds not fully captured by global normalization models.

The current predictive framework primarily isolates thermal volatility (LST Volatility) and hydric stress as primary drivers; however, natural apiary environments involve confounding biotic stressors—such as parasitic

mite infestations (*Varroa destructor*), viral pathogen loads, and systemic pesticide exposure—that interact non-linearly with thermal stress.

Although Sentinel-3 SLSTR and MODIS MOD11A1 data products offer exceptional longitudinal depth, their spatial resolution presents limitations when evaluating micro-climatic thermal anomalies at ultra-local apiary scales without dense ground-station calibration arrays.

While a 24-year historical extraction provides strong macro-environmental context, multi-decadal evolutionary adaptation rates of social insect colonies under rapid anthropogenic warming remain an evolving variable requiring continued longitudinal tracking.

Recommendations

To translate these theoretical discoveries into tangible protections for commercial and smallholder beekeeping operations, several strategic recommendations are advanced:

Commercial apiarists and agricultural extension services should integrate computer-vision diagnostic pipelines utilizing the established symmetry threshold $S_{crit} < 0.6214$ to perform routine, non-destructive comb frame scans before visible colony workforce depopulation occurs.

Apiaries situated in high thermal volatility nodes (such as semi-arid and boreal extremes) should implement proactive structural management—including strategic shade placement, insulated hive designs, and enhanced ventilation—to dampen acute land surface temperature spikes.

Because thermal stress forces inefficient material allocation and inflates the wax-to-storage ratio WSR, beekeepers must provide supplemental nutritional provisioning during high-stress seasonal windows to offset the heightened metabolic waste expenditure E_{therm} of worker bees.

Environmental ministries and agricultural agencies should incorporate automated structural health metrics and bio-climatic volatility mapping into national pollinator protection programs to safeguard vital pollination services across Solanaceae, Rosaceae, and global food production matrices.

Future Scope

Future studies should expand the multi-tiered framework to integrate real-time biotic pathogen tracking (e.g., Varroa mite load dynamics and viral RNA titers) alongside thermal volatility vectors to model synergistic collapse pathways.

Translating the YOLOv11-seg and OpenBeePose architecture onto resource-constrained edge microcontrollers (such as ESP32-S3 hardware deployments) will enable real-time, in-hive video processing and instant automated alerts for apiarists.

Exploring the intersection of quantum tunneling in olfactory receptors and vibronic resonance in bee sensory systems under thermal stress may uncover deeper biophysical mechanisms governing architectural construction fidelity.

Extending the mixed-effects predictive models across future IPCC climate scenarios (SSPs) will allow researchers to map global pollinator vulnerability trajectories decades in advance, guiding worldwide biodiversity conservation and food security policies.

Declarations

Ethics statement
Not Applicable.

Clinical trial number
Not Applicable.

Consent to Publish

Not Applicable.

Consent to Participate

Not Applicable.

Competing interest

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

Authors' contributions

M. R. K. Pathan: Conceptualization, Methodology, Data Analysis, Data Curation, Writing & Original Draft and Validation.

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Data availability statement

The data used in this study were obtained from publicly accessible biodiversity and environmental data repositories. Bee-occurrence records were primarily accessed through the Global Biodiversity Information Facility (GBIF), with the original publishing institutions and datasets retained for data provenance; supplementary georeferenced bee observations may be obtained from iNaturalist where applicable. Meteorological and land-surface variables were obtained from the ERA5-Land reanalysis, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and distributed through the Copernicus Climate Change Service (C3S) Climate Data Store. All records were subjected to taxonomic, geographic, temporal, duplication, and coordinate-quality screening before analysis. The processed analytical dataset, data-cleaning procedures, and derived variables generated during this study are available from the corresponding author upon reasonable request, subject to the licensing conditions of the original data providers. All original datasets remain accessible from their respective public repositories.

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