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Ecological Drivers of Swiftlet House Sustainability in Bangka Belitung: Habitat-Prey and Microclimate Connections in Coastal and Urban Context

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ABSTRACT

Swiftlet nest production depends on free-flying birds that forage outside buildings. This study maps the structural positions of ecological and institutional factors within the swiftlet house system in the Bangka Belitung Islands, and formulates a testable ecological pathway. The study design uses a case study approach combining focus group discussions with 19 participants, observational reconnaissance in coastal and urban contexts, single-time temperature and humidity readings, document review, and Cross-Impact Matrix Multiplications Applied to Classification (MICMAC) analysis of 14 variables. Habitat recorded the strongest outgoing influence (23); weather had an outgoing influence of 15 and a dependence of 0; governance occupied a linkage position; while business actor income and local government revenue had dependencies of 28 and 27 respectively. The matrix contained 118 actual or potential relationships with a fill rate of 60.20%. These results indicate a structural arrangement that places habitat and weather upstream, governance as a mediator of ecological pressure, and population and economic outcomes downstream. The habitat–prey–insect–microclimate–population pathway

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represents a theoretical synthesis, not a relationship measured directly in the matrix. Readings of 25 °C/79% in the coastal context and 32 °C/73% in the urban context reflect conditions at the time of observation. This study produces propositions to be tested through longitudinal monitoring of land cover, aerial insects, weather, building microclimate, occupancy, reproduction, nest production, and harvest intensity.

Keywords: *Aerodramus fuciphagus*; Habitat; Aerial Insect Prey; Microclimate; Adaptive Governance; MICMAC; Bangka Belitung

1. Introduction

Swiftlet nests are produced by *Aerodramus fuciphagus*, an aerial insectivore distributed across Southeast Asia [1]. Swiftlet houses have proliferated on the surfaces of buildings, cliffs, embankments, and protected areas, as well as in rooms that can be managed, yet these structures do not provide an energy source for the birds. Swiftlets obtain insects above water bodies, wetlands, vegetation, forests, agricultural land, and burned land. Nest production sustainability therefore depends on the relationship between buildings and the natural landscape where the birds forage [2,3].

The shift from cave harvesting to swiftlet houses expands economic activity while relocating the system of wildlife utilization into the landscape [4,5]. Buildings can increase roosting space, while impervious surfaces, vegetation fragmentation, pesticides, artificial light, noise, and pollution can alter prey availability and flight space quality. Recent studies indicate that urbanization filters tropical bird communities and changes insect abundance; vegetation and blue-green space connectivity become key habitat features in fragmented landscapes [6–8].

The Bangka Belitung Islands consist of main islands and small islands directly facing the sea, with a tropical maritime climate, featuring a mosaic of waters, wetlands, vegetation, settlements, roads, and trade centers [9]. Land cover change in Belitung over the past two decades indicates that the landscape is dynamic [10]. For swiftlets, these changes have the potential to affect insect emergence sites, travel direction and cost, heat exposure, humidity, wind, and anthropogenic disturbance. Coastal and urban contexts in this study are treated as two landscape conditions, not as two statistical populations being compared.

Geographically, this island province is located on the eastern side of Sumatra and is composed of Bangka Island, Belitung Island, and hundreds of small islands. Coastlines, bays, swamps, short rivers, former mining pits, ponds, shrubs, and settlement areas form a dense habitat mosaic. The maritime climate produces high humidity, rainy seasons and dry seasons that are still buffered by interannual variation, and sea wind influences on daily conditions. For aerial insectivores, the ecological value of an area is determined not only by vegetation extent, but also by the balance between water bodies, air, wetlands, flying space, and foraging corridors. Regional statistics emphasize that population concentration and service activities are higher in urban centers, while coastal and rural areas maintain a greater mix of natural habitat [9].

Landscape change in Bangka Belitung is linked to a long history of tin extraction, settlement expansion, road network development, trade center growth, as well as changes in land cover and vegetation. Mining footprints produce pits and open land that can create new water habitats, but can also reduce canopy, alter drainage, and break connectivity between terrestrial and aquatic habitats. Because insect and bird responses depend on quality, not merely presence, these disturbances are not automatically offset by the existence of open water. This reading is important for swiftlet houses, which should be viewed as building units detached from the history of landscape change around them [10].

The growth of swiftlet houses adds another layer of change. Buildings initially concentrated in certain locations develop following business opportunities, road access, trade centers, and building availability. Their continuity depends on birds' dependence on natural prey; their change depends on the provision of artificial roosting space through human management. Thus, an increase in the number of buildings is not always identical to an increase in carrying capacity. If prey habitat declines, the addition of roosting space can produce competition for food, occupancy that is not stable, or buildings that are not productive. The historical relationship between landscape transformation and business expansion

becomes an analytical entry point for placing habitat and weather before economic outcomes [4,5,10].

Swiftlet house studies have examined feed, house design, temperature, humidity, harvest, product quality, and business economics [2,5,11]. However, three gaps remain visible. First, building-scale research rarely connects microclimate within the building to landscape composition and aerial insect supply. Second, sectoral review lines rarely distinguish ecological factors located upstream from variables that merely transmit or receive influence. Third, governance is often treated as an explanatory center, whereas energy and prey for swiftlets originate from biophysical processes.

The research problem lies in the mismatch between sustainability claims and the types of evidence commonly used. Success is often assessed from the presence of houses, nest counts, or income, while population conditions, prey balance, habitat quality, and harvest pressure are rarely observed simultaneously. At the same time, institutional approaches explain rules and coordination but do not by themselves demonstrate the biological pathways that sustain colonies. A framework is needed that places ecological processes as prerequisites, identifies institutions as influencing components, and positions economic outcomes as consequences that must be tested, not as the sole indicator of sustainability.

2. Theoretical Foundation

2.1. Social-Ecological Systems and Business Outcomes

The sustainability of wildlife utilization requires biological resource renewal and maintenance of the ecological processes that support it [12,13]. In the swiftlet house system, the resource units are birds and nests; the resource system includes buildings and the foraging landscape; weather and landscape change are external drivers; while rules, registration, monitoring, and harvest practices regulate human responses. Income cannot be used as a single proxy for population sustainability because price, cost, nest quality, and harvest intensity can change revenue without improving biological conditions.

Swiftlet house success is understood as a sequence of outcomes. Landscape and weather conditions influence insect emergence and flight activity; prey and external weather interact with openings, ventilation, temperature, and humidity of the building; these conditions can affect visitation, occupancy, reproduction, and nest count. Income and government revenue are located further downstream and are influenced by market and administrative mechanisms [5,11].

2.2. Complementarity of Prey Habitat and Microclimate

An ecological niche refers to the set of conditions and resources that enable an organism to survive and reproduce [14]. In swiftlets, these resources are spatially separated. Buildings provide nesting habitat, while the landscape provides prey and flying space. The principle of landscape complementation explains that a species can persist when habitats providing different resources are within reachable distance and remain connected [15]. Petkliang et al. [3] found intensive use of water bodies, forests, and open rice fields that also store biomass of major prey groups.

As central-place foragers, swiftlets bear travel costs between the house and foraging patches [16]. Distance, connectivity, wind, building density, and the distribution of insect-producing habitat can alter these costs. Weather operates through trophic pathways: rain, temperature, humidity, and wind influence insect emergence and activity, and then prey conditions influence reproductive timing. Synchrony of rainfall, insect biomass, and chick provisioning periods has been reported in Germain's swiftlet [17].

Building microclimate functions as a filter at the microhabitat scale. Temperature, relative humidity, light, ventilation, and position within the space shape the suitability of nest attachment sites and the conditions experienced by eggs and chicks. The clustered distribution of nests in certain parts of swiftlet houses indicates that a single building average is insufficient to describe colony room selection [18].

The complementarity model proposed links landscape composition and connectivity to insect production capacity; weather to insect biomass and flight activity; prey to foraging efficiency; building microclimate to nesting suitability; and governance to habitat protection, pesticide control, harvest regulation, building standards, monitoring, and harvest. The model is an analytical synthesis. Prey, microclimate, occupancy, reproduction, and nest production variables are not assessed separately in the MICMAC matrix.

At the landscape scale, prey availability is a function

of habitat composition, configuration, and quality. Two landscapes with the same vegetation percentage can provide different outcomes if vegetation patches are isolated, far from swiftlet houses, exposed to pesticides, or not near aquatic habitats that support larval stages. Blue–green connectivity is important because it is required as a functional property: it influences prey population connectivity and obstacles that must be traversed by birds. Evidence on trophic connectivity between forests and agricultural land for foraging birds indicates that organism flow functions as a life-support controller across land-use boundaries[15].

At the building scale, temperature and humidity do not operate as single figures. Vertical gradients, distance from the entrance hole, ventilation, wall material, nest density, solar exposure, and air circulation can produce spatial variation within the house. Single-point measurements at one location fail to capture maximum temperature, duration of extreme conditions, or differences between day and night. Therefore, microclimate suitability should be analyzed as a temporal and spatial distribution, then linked to active nest locations, reproductive success, and occupancy changes[18].

Climatic mechanisms are also cascading. Changes in rainfall patterns can affect inundation and larval habitat productivity; temperature changes insect development and emergence timing; strong wind and rain limit flight activity; while drought can increase thermal stress inside buildings. Its impact on nests does not necessarily appear on the same day because prey conditions earlier influence foraging, individual condition, chick provisioning, and reproductive timing. Literature on aerial insectivores indicates that annual reproduction can follow weather variation through pathways involving prey availability[17,19].

The social-ecological system framework places governance as a mechanism linking information, rules, actors, and responses to environmental change[12,13]. In the context of swiftlet houses, these positions include the ability to record building locations, integrate landscape and weather information, manage disturbance, provide technical guidance, and connect harvest practices with biological indicators. Effective governance does not replace habitat, but can reduce pressure, maintain connectivity, and prevent short-term economic decisions from damaging reproductive conditions.

The research flow needs to be presented to clarify the separation between system boundary setting, structural assessment, and ecological testing. **Figure 1** shows how initial information, variable identification, focus group discussion, and MICMAC processing are placed within two analytical cycles.

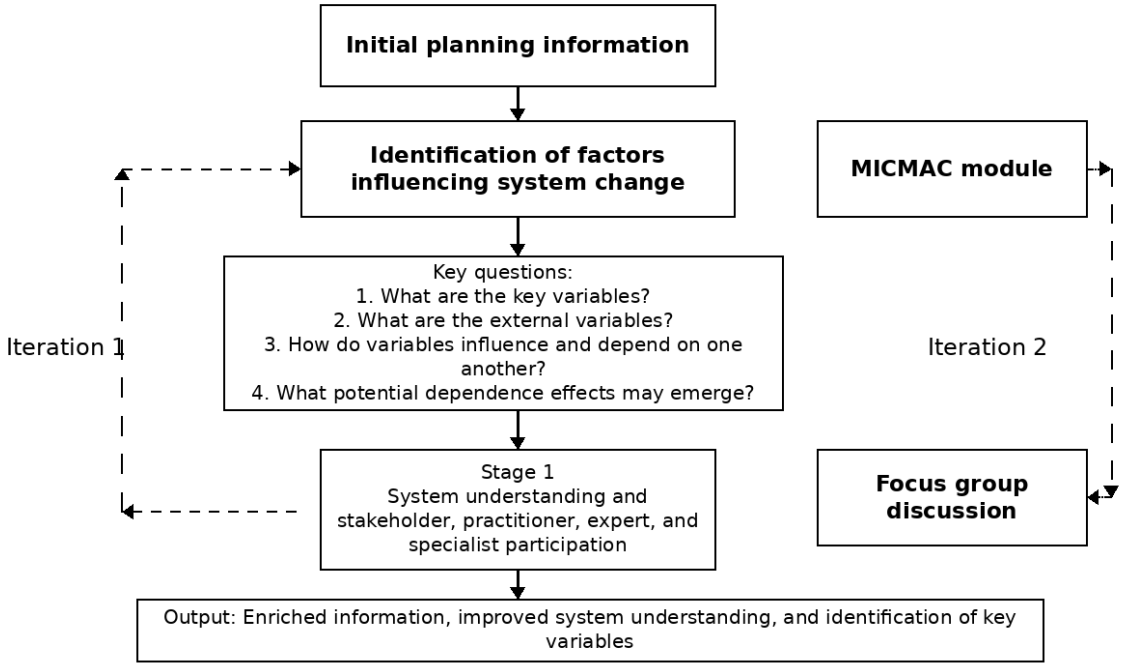

Figure 1. Research flow.

Source: Adapted from Arcade et al.[19] and Godet[20].

Figure 1 explains that the first cycle builds system understanding and selects variables based on initial information, stakeholder knowledge, and ecological context. The second cycle assesses relationships between components through group discussion and MICMAC. The structural results are then checked against field evidence and literature. This sequence limits MICMAC to a relationship mapping tool, not a substitute for measurement of prey, microclimate, occupancy, or reproduction.

3. Methods

3.1. Design and Study Area

The study uses an embedded case study. The main case is the social-ecological system of swiftlet houses in the Bangka Belitung Islands; coastal and urban contexts serve as reconnaissance observation units. The primary analysis is a 14 × 14 direct influence matrix constructed through focus group discussions. Landscape observations, building condition documentation, and temperature and humidity readings are used only to provide context. A single consensus matrix does not allow estimation of coastal–urban differences.

Data collection took place on 8 May 2025 in Pangkalpinang. The meeting was chosen to gather actors familiar with swiftlet house conditions across various locations in the province. Two field contexts were purposively selected because they exhibit differences in building density, proximity to water, open space, and maintenance conditions. This selection is not intended as a sample of swiftlet houses representing all coastal and urban areas.

The MICMAC unit of analysis is the relationship between concepts within the provincial system boundary, not individual swiftlet houses. Therefore, 19 participants served as sources of structural assessment, while coastal and urban locations only provided context for the terms habitat and microclimate. There is no house sampling frame, selection probability, or location replication that would allow statistical generalization. Differences in soil, hydrology, and land cover are needed as candidate habitat attributes requiring separate measurement, not as variables that have been compared in this study.

The coastal context is qualitatively characterized by proximity to water and greater open space, while the urban context exhibits higher building density and built surfaces. This classification does not use coastal distance thresholds or quantitative urbanization indices. Therefore, the terms coastal and urban describe the observation setting, not an experimental treatment. Conclusions are not extrapolated to state that all coastal houses are more suitable or all urban houses are less suitable.

3.2. Participants

The discussion involved 19 participants: 10 swiftlet house business actors, 6 government representatives, 2 academics or researchers, and 1 community representative. Business actors contributed knowledge on house operations, harvesting, and business conditions; government representatives understood licensing, spatial planning, services, and supervision; academics or researchers provided ecological and methodological considerations; community representatives conveyed experiences regarding the residential environment and social relations. Participants were purposively selected according to knowledge function, not to produce statistical representativeness.

The participant composition shows a dominance of operational and administrative knowledge: business actors and government representatives total 16 out of 19 people, while the rest are represented by academics/researchers and community representatives. This compositional imbalance may influence the definition of direct relationships, especially when invisible ecological processes must be compared with economic and regulatory relationships experienced daily. The analysis therefore does not treat the consensus matrix as a balanced representation of all types of knowledge. It is treated as a product of group deliberation with an openly declared distribution of expertise.

Relevant experience is defined by involvement in swiftlet house management, government services and supervision, academic study, or community environmental experience. Individual length of experience was not recorded in the analytical database and thus was not used as a weighting of assessments. Each consensus score is treated equally, without weighting by position or group. This approach allows the unification of views, but cannot show whether a particular value was primarily driven by one category of participants.

A single matrix was formed through deliberation of all participants. The available materials do not contain individual scoring sheets or separate matrices per group. Therefore,

the study does not calculate Kendall's W and does not conclude that consensus eliminates differences of opinion. The absence of pre-consensus data limits the assessment of inter-participant reliability.

3.3. Variables and Instruments

The instruments consist of a discussion guide, variable identification sheets, a variable dictionary, observation sheets, and a direct influence matrix. Fourteen variables were retained according to the initial assessment. The definitions used during the discussion are general and functional. Habitat (EK3) refers to environmental conditions where swiftlets live and forage; weather (EK4) includes temperature, humidity, rain, wind, and seasonal variation; swiftlet population (EK2) refers to the presence and relative number of birds; research (EK1) refers to knowledge production and monitoring. Details of land cover, connectivity, insect prey, light, noise, and microclimate position constitute analytical operationalization based on literature after mapping. The matrix was not reassessed with these expanded definitions.

The MICMAC analysis begins with the establishment of variables representing the main elements of the swiftlet house system in the Bangka Belitung Islands. The fourteen variables in **Table 1** were formulated through focus group discussions by considering relationships between ecological conditions, economic activities, institutions, and the social-political environment. Variable codes are used consistently in the direct influence matrix, the influence–dependence map, and the interpretation of the structural position of each element.

Table 1. Research variables and MICMAC codes.

No.	Variable	Code	Dimension
1	Research	EK1	Ecological
2	Swiflet Population	EK2	Ecological
3	Swiflet Habitat	EK3	Ecological
4	Weather	EK4	Ecological
5	Business actor income	EN1	Economic
6	Local government revenue	EN2	Economic
7	National business climate	EN3	Economic
8	Global economic conditions	EN4	Economic
9	Regional business climate	EN5	Economic
10	Regulation	KL1	Institutional
11	Governance	KL2	Institutional
12	National political conditions	SP1	Social-political
13	Regional political conditions	SP2	Social-political
14	Global political conditions	SP3	Social-political

Source: Focus group discussion results and primary data processing, 2025.

Table 1 groups variables into four dimensions. The ecological dimension includes research (EK1), swiftlet population (EK2), swiftlet habitat (EK3), and weather (EK4). In structural reading, habitat and weather are ecological conditions upstream; swiftlet population is a biological response; while research provides knowledge and feedback for management. This grouping does not mean that the four constructs have been measured through the same biophysical indicators.

The economic dimension consists of business actor income (EN1), local government revenue (EN2), national business climate (EN3), global economic conditions (EN4), and regional business climate (EN5). Income variables are placed as system outcomes because their values are formed through interactions of nest production, quality, price, cost, market access, registration, and regional revenue administration. The institutional dimension includes regulation (KL1) as formal rules and governance (KL2) as the implementation of coordination, registration, monitoring, technical services, compliance, and adaptation. The social-political dimension includes national (SP1), regional (SP2), and global (SP3) political conditions, which can alter policy stability, trade, investment, and management implementation capacity.

3.4. Assessment Procedure and Field Evidence

Participants assessed whether a change in a row variable could directly change a column variable within the

agreed system boundary. The rating scale is 0 for no explainable direct influence, 1 for weak, 2 for moderate, 3 for strong, and P for potential influence. Diagonal cells are assigned zero. Contested values are re-discussed by examining the direction of the relationship and the existence of mediators. The final score is group consensus [19,20].

A direct relationship is defined as a change in variable A that can change variable B without first changing a third variable already listed in the system. Potential relationships are used when the pathway is not yet dominant under the conditions at the time of discussion but is expected to become relevant due to policy, market, or environmental change. Emphasis on the existence of mediators is important because an overly dense matrix can obscure the difference between direct influence and cascade effects.

Score consolidation was carried out through open discussion until a single group value was reached. Variable pairs were evaluated within system boundaries for direct row-to-column effects. Scoring discrepancies were resolved during group deliberation by reviewing influence direction, timeframe, and mediating variables, supported by descriptive pathways. Relationships were classified as direct influences (variable A alters B without an intervening listed variable) or potential influences (currently non-dominant relationships expected to strengthen via policy, market, institutional, or environmental shifts). Final scores were established through deliberative consolidation rather than voting, arithmetic averaging, or status-based weighting.

This procedure produces a matrix that can be processed by MICMAC, but eliminates pre-consensus variation. Without individual assessment sheets, score deviation, proportion of agreement, and Kendall's W cannot be calculated. The absence of these measures means that consensus must be understood as a deliberative group decision rather than a statistical measure of individual rating uniformity.

The selection of 14 variables was based on their relevance to the four domains that emerged in system identification: ecological conditions, economic outcomes, institutional capacity, and social-political environment. Variables were retained if participants could explain their connection to swiftlet presence, business operations, government response, or external change. Soil, hydrology, insects, microclimate, occupancy, and reproduction were not assessed as separate constructs; these elements are therefore only used to elaborate mechanisms and test designs, not to add MICMAC results retrospectively.

Temperature and humidity were read once in one coastal context and one urban context. The available research archive does not record instrument brand, reading time, sensor position, calibration procedure, or replication. These values serve as background notes during the visit, not as mean estimates, ecological comparisons, or evidence that urbanization causes microclimate differences.

3.5. MICMAC Processing

Row sums indicate outgoing influence and column sums indicate dependence. Matrix multiplication traces indirect influence; stability is reached at the fourth iteration. Quadrants are separated using relative lines at the mean influence and mean dependence displayed in the MICMAC output. Variables with high influence and low dependence are read as drivers; high–high as linkages; low–high as dependent variables; and low–low as autonomous [19,20].

Weather was not predetermined as an exogenous variable. Zero dependence originates from the consensus that no other variable within the system boundary directly changes weather, while weather influences other elements. This interpretation is limited to the model boundary and does not negate anthropogenic influence on climate at a broader scale.

The reported analysis is based on matrix summaries, the influence–dependence map, and the direct influence network. The cell-by-cell matrix, complete numerical coordinates, and the ranking order of direct and indirect influences are not part of this study's analytical dataset. Therefore, the discussion does not estimate values from visual positions and does not make claims regarding rank changes that are not supported by numbers. These limitations reduce computational reproducibility and restrict interpretation to documented aggregate scores.

3.6. Research Ethics

Participation is voluntary, prior to the discussion, participants received an explanation of the research objectives, form of involvement, use of information, confidentiality of identity, and the right not to answer or to withdraw from participation. Informed consent was obtained before the activity began, and reporting was conducted at the group level

without linking assessments to participant identities. The study received ethical approval from the ethical committee at the university.

4. Results and Discussion

4.1. Matrix Structure

The direct influence matrix consists of 196 cells (14 × 14), including 14 diagonal cells set to zero in accordance with structural analysis procedures.

The matrix consists of 196 cells. A total of 78 cells are zero and 118 cells contain actual or potential relationships: 41 weak, 13 moderate, 43 strong, and 21 potential. The fill rate of 60.20% indicates a dense system. This density does not automatically mean that all relationships occur directly ecologically. It may also indicate that relationships through mediators were assessed as direct influence during deliberation.

The characteristics of the direct influence matrix are presented to show the data structure underlying the mapping of influence and dependence between components. **Table 2** summarizes the matrix size, intensity distribution of relationships, number of identified relationships, fill rate, and number of iterations to stability. This information is needed to assess the density of the system structure while establishing the limits of inference for MICMAC results.

Table 2. Characteristics of the direct influence matrix.

Indicator	Value
Matrix size	14
Iterations to stability	4
Zero values	78
Weak relationships	41
Moderate relationships	13
Strong relationships	43
Potential relationships	21
Connected cells	118
Fill rate	60,20%

Source: Focus group discussion results and primary data processing using MICMAC, 2025.

As summarized in **Table 2**, the system comprises 78 zero cells and 118 connected cells containing actual or potential relationships (41 weak, 13 moderate, 43 strong, and 21 potential). Evaluating connected cells against the total matrix yields a fill rate of 60.20% (or 64.84% when calculated over the 182 off-diagonal pairs). The 60.20% metric is retained following standard MICMAC output. This high density reflects a system where indirect pathways occurring through mediators—such as habitat influencing business income via insect prey availability, foraging activity, occupancy, reproduction, nest production, nest quality, market price, and operational costs—were often evaluated as direct influences during group deliberation. Non-zero relationships therefore denote perceived structural connectivity rather than direct ecological mechanisms.

The 21 potential relationships represent pathways that were non-dominant under conditions at the time of assessment but are expected to strengthen under changing ecological, institutional, economic, or socio-political conditions. Substantively, these pathways emerge when influence channels depend on contextual shifts—such as research gaining greater influence over governance if monitoring data are integrated into licensing, or regulation effectively mitigating habitat degradation if location compliance and pesticide controls are enforced. Potential relationships represent prospective structural capacity rather than historical impacts and cannot be aggregated with actual relationships to claim realized effects. Conversely, the high proportion of strong relationships (43 of 118) highlights strong perceived inter-component dependencies across the system.

MICMAC analysis in this study is interpreted strictly through documented aggregate metrics, including fill rate, iterations to stability, direct influence networks, and influence–dependency positioning. Among the variables, habitat (EK3) held the strongest outgoing influence (23), weather (EK4) recorded an outgoing influence of 15 with zero dependency (exogenous driver within model boundaries), governance (KL2) functioned as a relay variable (simultaneously receiv-

ing and transmitting influence), and business actor income (EN1) and local government revenue (EN2) recorded incoming dependency totals of 28 and 27, respectively, alongside swiftlet population (EK2), research (EK1), and regulation (KL1).

These figures reflect relative ordinal positions within stakeholder evaluations rather than physical quantities, probabilities, or causal ratios—a score of 23 for habitat, for instance, does not denote an effect 1.53 times larger than weather's 15. Matrix stability was achieved at the 4th iteration, indicating that the relative influence-dependency structure stabilized during matrix multiplication, which reflects model structural properties rather than inter-participant reliability or empirical validation.

As an example, the relationship between habitat and business actor income ecologically occurs through insect availability, foraging activity, occupancy, reproduction, nest production, quality, price, and cost. The separation between these pathways requires structural clarification as causal coefficients. A complete 14 × 14 matrix is needed as supplementary data so that each relationship can be examined and reproduced.

Stability at the fourth iteration indicates that the relative arrangement of influence and dependence no longer undergoes significant change in the matrix multiplication process. This stability relates to the structure of the model, not to inter-participant reliability or empirical validation. Rank changes between direct and indirect influence can only be reported after MDI and MII outputs at each iteration are matched with the original software archive.

The relative position of variables on the influence and dependence axes is presented in **Figure 2**. This map is used to distinguish driver, linkage, dependent, and autonomous variables based on the relative limits of the MICMAC output.

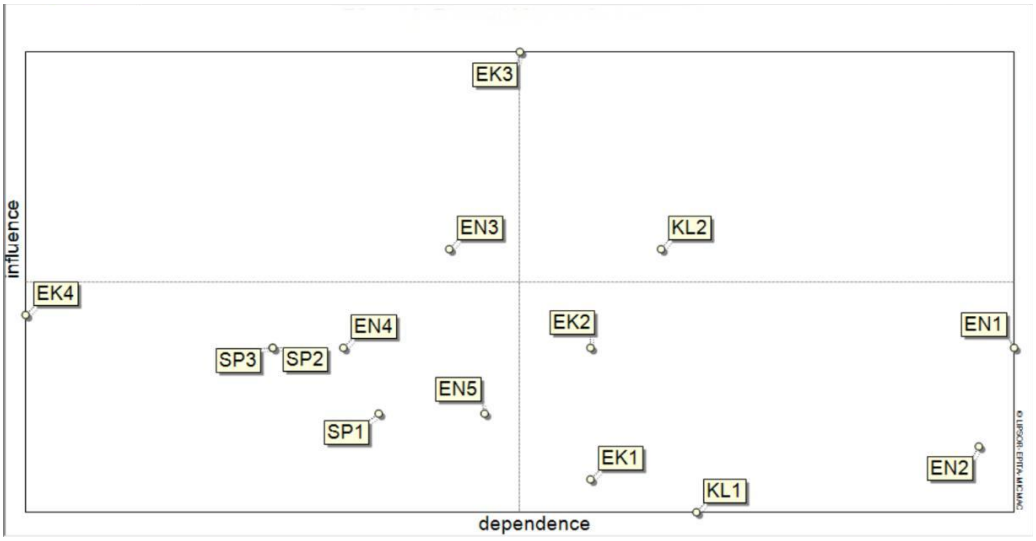

Figure 2. Direct influence and dependence map.

Source: Focus group discussion and MICMAC processing, 2025.

In **Figure 2**, habitat (EK3) recorded the highest outgoing influence, namely 23. Weather (EK4) had an outgoing influence of 15 and a dependence of 0. Governance (KL2) is in the linkage quadrant because it both receives and transmits influence. Business actor income (EN1) and local government revenue (EN2) had incoming influence scores of 28 and 27 respectively. These values are measures of position in the matrix, not economic units, opportunities, or impact coefficients.

The map places habitat and weather in the driver region, while governance is in the linkage position. Swiftlet population, research, regulation, business actor income, and local government revenue tend to be more dependent. Numerical coordinates other than the sums mentioned above are not available in the export archive and are not estimated from the map.

The direct influence network complements the quadrant map by showing the direction and intensity of relationships assessed between variables. **Figure 3** is presented to show the density of the structure as well as the pathways that form

the basis of the relationships in **Table 2**.

In **Figure 3**, lines and arrows represent the direction and strength category of influence entered into the matrix. The density of relationships around habitat, weather, governance, population, regulation, and economic variables indicates that the system is perceived as interconnected. However, the network does not prove temporal order or biological mechanisms. Relationships that ecologically require mediators are still interpreted through prey, microclimate, occupancy, reproduction, and production pathways.

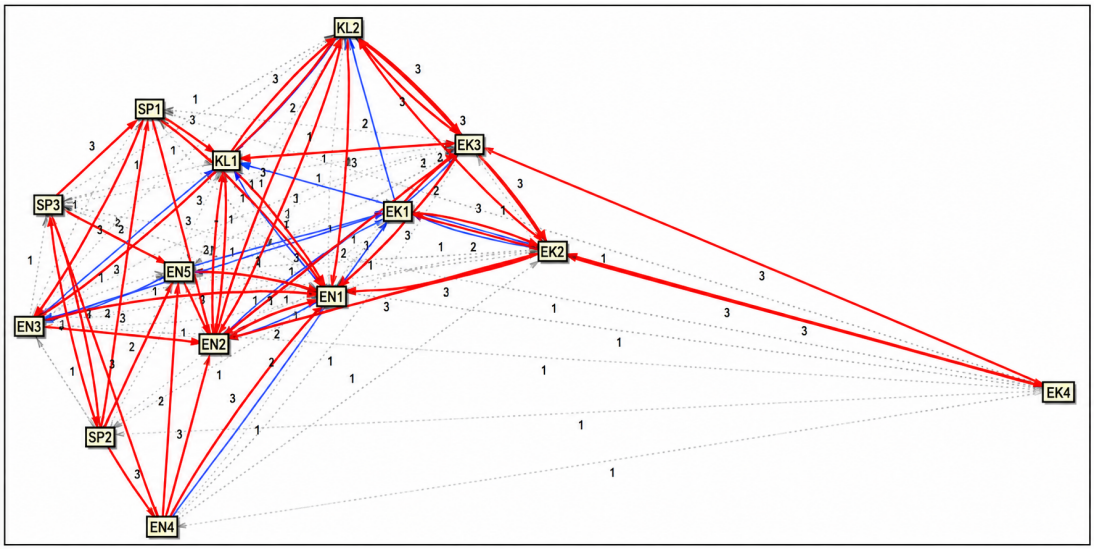

Figure 3. Direct influence network between variables.

Source: Focus group discussion and primary data processing using MICMAC, 2025.

4.2. Habitat as Driver and Prey as Mediator

The outgoing influence of habitat of 23 indicates that participants assessed changes in habitat conditions also affecting many other elements. Biologically, the most plausible pathway occurs through aerial insects and the availability of foraging space. Water bodies, wetlands, forests, rice fields, and vegetation produce different prey communities[2,3]. Canopy cover, fragmentation, pesticides, artificial light, and noise can reduce or displace prey and alter flying space[6–8].

The meaning of habitat in the results is limited to the definition used by participants, namely environmental conditions for swiftlet life and foraging. More detailed interpretation—proportions of water, vegetation, agriculture, impervious surfaces, connectivity, light, noise, and pesticide exposure—is an operational device for further research. This limitation is important because the initial scores cannot be considered a separate assessment of each landscape component. The finding that habitat is central does not mean that all landscape components are equally related to the overall habitat construct.

The Bangka Belitung context reinforces the need to distinguish prey-producing habitat from roosting habitat. Pits, swamps, coastal vegetation, gardens, rice fields, shrubs, and open space can produce insects with different compositions, while swiftlet houses only provide resting and nesting places. If one component increases while another decreases, biological outcomes cannot be predicted from building numbers alone. The complementarity model predicts that occupancy is more stable when nesting sites can be reached from productive foraging patches and are connected[3,15].

Anthropogenic exposure needs to be included without turning it into an unmeasured claim. Pesticide use can reduce insect availability; artificial light can alter insect distribution and activity; noise near settlements can disturb flying space; while building maintenance affects ventilation and microclimate. This study does not measure the dose or response of these factors. It only indicates that the strong influence of habitat encourages researchers to place mediators that can be explicitly observed.

The matrix does not include aerial insects as a separate variable. Therefore, the EK3 score does not prove the pathway from habitat to population. The empirical finding

of this study only states that habitat occupies a structural position upstream. The habitat → insect → foraging activity → occupancy and reproduction → nest production pathway is a mechanism supported by literature and needs to be tested with far-reaching monitoring, standard insect traps, bird counts, and nest recording.

4.3. Weather, Microclimate, and Temporal Dynamics

The position of weather as an influential variable with zero dependence is consistent with the system boundary used. Rain can change aquatic habitat and insect emergence; temperature, humidity, and wind affect insect activity as well as the ability of swiftlets to forage. Production responses may be delayed because influence must pass through prey availability, body condition, reproductive time, and nest formation[17,21].

During field visits, the coastal context recorded approximately 25 °C and relative humidity of 79%, while the urban context recorded approximately 32 °C and 73%. These two readings do not indicate daily or seasonal averages, do not apply physiological thresholds, and do not support the claim that urban areas are worse than coastal areas. Their function is limited to showing that temperature–humidity measurements can differ between positions and elevations, inside and outside buildings, during at least one annual cycle.

These readings also cannot be used to identify swiftlet thermal preferences. Instantaneous values can be influenced by visit time, weather that day, sensor position, air circulation, and building material characteristics. Without calibration and replication, a difference of seven degrees Celsius only indicates that the two points were not in the same condition at the time of observation. The presentation of values as limited context, accompanied by metadata, prevents shifting from descriptive observation to comparative evidence.

An adequate test design requires automatic recorders with fixed intervals in several zones of each building, one external sensor as a comparator, calibration checks before and after installation, and recording for at least one annual cycle. Houses need to be stratified by building type, age, connectivity level, vegetation/water cover, and management conditions. These data are then paired with daily weather, insect biomass, bird entry–exit counts, active nests, reproductive indicators, and harvest timing.

4.4. Governance as Linkage

Governance receives pressure from business development, complaints, habitat change, research information, and political conditions; at the same time it influences registration, location planning, technical assistance, monitoring, compliance, and adaptation. The high–high position is therefore more appropriately read as a linkage rather than an initial source of ecological change. Governance can reduce exposure or vulnerability, but does not directly produce rainfall and prey[13].

Regulation and governance need to be distinguished. Regulation provides formal rules regarding location, buildings, disturbance, environment, and operations. Governance determines whether these rules are translated into coordination, data, inspection, guidance, habitat protection, and correction of harvest practices. The more dependent position of regulation does not mean that rules are unimportant; the formation of rules itself responds to business growth and territorial pressure.

4.5. Cross-Scale Interventions and Climate Change

Local interventions can link house registration with maps of water bodies, vegetation, impervious surfaces, pesticide use, and residential complaints. District/city governments can regulate location density, ventilation, sound disturbance from calling devices, and harvest reporting. At the provincial level, monitoring of land cover, wetlands, blue-green corridors, and weather can be combined with changes in house occupancy. National policy is relevant through wildlife trade standards, product safety, spatial planning, ecosystem protection, pesticide control, and climate information systems.

At the local level, the first priority is to build a database of swiftlet house locations and conditions. House coordinates can be linked to land use zones, noise complaints, building density, distance to water bodies, and vegetation cover change. This information enables risk-based supervision: houses in areas with high fragmentation, large heat exposure, or residential conflict can receive more intensive monitoring. Local policy does not need to declare all urban areas unsuitable; it needs to recognize combinations of attributes that increase ecological and social risk.

At the provincial level, integration of hydrological, weather, land cover, pesticide use, and production data can detect whether occupancy declines are concentrated in certain seasons or landscapes. Regional interventions can also protect wetland networks and vegetation corridors that cross district/city boundaries. Because swiftlets move beyond administrative boundaries, policies that only regulate buildings without considering the cross-regional landscape risk displacing, rather than resolving, ecological pressure.

At the national level, traceability standards, product health, wildlife protection, chemical control, and climate information shape business incentives. Export requirements emphasizing quality and traceability can be used to encourage registration and harvest recording, but do not automatically guarantee population sustainability. Ecological indicators need to be included so that administrative compliance does not replace monitoring of habitat, reproduction, and harvest intensity.

Climate change introduces additional uncertainty regarding habitat quality, insect emergence, building microclimates, and seasonal conditions for swiftlet foraging activities. IPCC assessments indicate that shifts in temperature, precipitation patterns, and extreme weather events interact with exposure levels and local adaptive capacity [22]. Regional environmental statistics provide essential context regarding land cover changes, hydrology, and environmental pressures in Bangka Belitung [23–25]. Evidence concerning forest–farmland trophic connectivity and swiftlet habitat suitability further supports the need for distinct observations of water bodies, vegetation, aerial insects, and foraging space configurations [26,27].

Biodiversity change does not always proceed uniformly between taxa and regions. Time-series synthesis indicates that the direction and magnitude of invertebrate community change depends on land-use context, climate, and monitoring quality [28]. Global terrestrial assessments also place habitat, water, and food connectivity as the main drivers of landscape management, not as separate sectors [29]. In the swiftlet house system, this principle means that water bodies, vegetation, insects, microclimate, business practices, and the residential environment need to be read as one chain of relationships. Natural resource and forest reports emphasize that changes in material use and land cover require management that links conservation, restoration, and economic needs [30,31]. The status of migratory birds globally also reinforces the importance of maintaining habitat quality along species movement ranges, although swiftlets in this study were not analyzed as migratory populations [32].

At the Indonesian scale, environmental statistics, seasonal information, and forestry statistics provide a basis for placing local Bangka Belitung changes within broader regional variation [33–35]. Climate and development reports indicate that high risk, land-use transformation, and development choices need to be read together because their impacts differ by region and adaptive capacity [36]. IPCC synthesis emphasizes that high risk passes through interactions between climate, exposure, and vulnerability, so it requires combining monitoring, ecosystem-based adaptation, and governance that can learn from change [37]. Without these studies, swiftlet house literature tends not to replace local measurements; its function is to provide a comparative series for rainfall, temperature, land cover, hydrology, and habitat change that can then be paired with insects, building microclimate, occupancy, reproduction, and nest production.

Integrating social and ecological evidence requires design discipline. Urban studies place evolutionary change and ecology as outcomes of organism interactions with city form [38], while policy studies indicate that coordination, coherence, and integration of actors across sectors help produce consistent responses [39]. Systems analysis helps emphasize problem boundaries and relationships between components [40], while adaptive governance explains the importance of learning, feedback, and adjustment to change [41]. Purposive informant selection can capture relevant knowledge variation, but cannot produce statistical representativeness and still requires reporting of the relative composition of selected participants [42,43]. Case studies provide the logic of connection between questions, evidence, and inference [44]. Findings on global insect abundance decline further remind us that prey trends cannot be assumed uniform without local measurement [45].

Soil types are relevant insofar as they form traceable processes. Texture, drainage, moisture, organic matter content, and disturbance level can affect vegetation and the ability of land to store water; these conditions subsequently affect larval habitat and adult insects. In post-mining land, soil–water–vegetation relationships may differ from gardens, natural swamps, rice fields, or built-up areas. However,

this study did not collect soil samples or analyze physical-chemical soil properties. Soil types are therefore used as an explanation of conditions at the habitat score level, but not as a component that needs to be added to location stratification and hydrological mechanism testing.

Hydrology needs to be recorded through water body type, extent and duration of inundation, water level change, water quality, and its connection to the landscape. Permanent pools, seasonal inundation, urban drainage, swamps, and coastal waters do not always produce the same insect community. Insect sampling needs to be paired with water attributes so that associations between swiftlet houses and water bodies are not reduced to nearest distance. Spatial analysis can then test whether combinations of water extent, quality, and connectivity explain prey biomass better than coastal–urban categories.

Biological sustainability needs to be assessed with a set of indicators different from business performance. Condition indicators can include occupancy, number of active nests, eggs and chicks, reproductive success, and stability of bird activity. Pressure indicators can include habitat loss, pesticide exposure, extreme heat, noise, and harvest intensity. Response indicators include habitat protection, business compliance, harvest records, monitoring, and restoration of problematic locations. Production and income remain important, but they must be read alongside population conditions so that increased harvest is not considered an improvement in sustainability.

The impact of intervention cannot be assessed from the issuance of regulations alone. Evaluation requires baseline conditions, implementation time, comparable groups or locations, compliance indicators, and ecological outcomes. If registration policy is implemented in stages, changes in data quality, monitoring, and household harvest practices can be compared before and after implementation. If corridor protection is applied in a certain area, changes in insects and occupancy can be compared with similar surrounding areas that have not yet received intervention. A quasi-experimental design of this kind is more appropriate for assessing effectiveness than interpreting the position of governance in MICMAC as direct policy impact.

Climate change can shift the frequency of heat, rainfall patterns, wind, wetland hydrology, and insect phenology. Its impact on swiftlets cannot be inferred from daily measurements. Testing requires a series of daily weather, continuous microclimate, repeated insect sampling, and occupancy and reproduction data with time lags. Soil is not measured as a separate construct; the influence of soil type is only worth testing through its connection to hydrology, vegetation, insect habitat productivity, and land use change.

4.6. Chain of Evidence and Test Propositions

The chain of evidence in **Table 3** links each proposition with the MICMAC score or position, the proposed mechanism, and the limits of inference. This presentation prevents momentary observations, participant assessments, and literature evidence from being combined as a single type of evidence.

Table 3 shows that the strongest empirical support of the study lies in the structural position of variables: habitat has an outgoing influence of 23, weather has an influence of 15 and a dependence of 0, governance is in a linkage position, while EN1 and EN2 receive influences of 28 and 27 respectively. The habitat–prey–population mechanism, weather–microclimate–reproduction, and governance–adaptive response remain propositional because ecological mediators and instrument effectiveness have not been measured longitudinally.

Three propositions can be tested. P1: a higher proportion and connectivity of prey-producing habitat is associated with higher insect biomass and more stable occupancy. P2: weather variation affects occupancy and production through insect activity and microclimate with seasonal lags. P3: governance capacity moderates these pathways through location planning, habitat protection, pesticide control, monitoring, building management, and harvest practices. These propositions are derived from combining MICMAC structure and theory; they are not effect estimates from the current research data.

The validity of interpretation depends on the correspondence between the type of evidence and the type of statement. MICMAC scores support statements about the structural perceptions of the group; field observations support descriptions of the context observed; sensor readings support the condition of two points at a certain time; while literature supports the general plausibility of a mechanism. None of these types of evidence separately can estimate local causal effects. Therefore, claims in this study are formulated in a

tiered manner: 'occupies a position' for MICMAC output, 'observed' for field context, 'recorded' for temperature and humidity, and 'proposed' for ecological mechanisms. This limit of evidence maintains that the strength of conclusions is commensurate with the supporting data.

Construct validity is primarily limited by the breadth of the terms habitat, weather, population, research, and governance. Constructs that are broad at the system mapping stage are useful because they capture knowledge across sectors, but are less adequate to distinguish proximal processes. Habitat, for example, can include land cover, water quality, connectivity, pesticides, and disturbance; population can refer to regional abundance, activity around the house, or occupancy; governance can include registration, coordination, inspection, and technical assistance. Further testing must decompose these constructs into indicators that do not overlap, without changing the initial score already debated in the matrix.

Table 3. Chain of evidence and limits of inference.

Proposition	MICMAC Evidence	Empirical Context	Mechanism	Limits of Interpretation
Habitat is a system driver	EK3 has an outgoing influence score of 23 and is in the driver position	Differences in microclimate and spatial characteristics between coastal and urban areas; building management in urban areas is not uniform	Habitat supports insect prey, foraging space, occupancy, and production potential	No measured comparison is available between habitat, population, and production
Weather is an exogenous driver	EK4 has an outgoing influence score of 15 and an incoming score of 0	Temperature and humidity differ in the coastal and urban contexts observed	Weather is related to prey availability, foraging patterns, building microclimate, and harvest stability.	The relationship has not been tested using weather and production time series.
Governance is a linkage variable	KL2 is in the linkage quadrant	Locations are not fully planned; not all businesses are registered; management and downstream processing remain limited	Governance links ecological conditions, business management, data, services, and outcomes.	The study does not measure institutional effectiveness or the performance of specific instruments.
Regulation is a dependent variable	KL1 is in the dependent variable group	Regulatory responses develop alongside business growth and territorial problems	Regulation is an institutional outcome as well as a source of formal feedback.	A dependent position does not mean regulation is unimportant
Research is a dependent variable	EK1 is in the dependent variable group	Research needs to develop as a response to habitat, technical, and institutional problems	Knowledge can provide feedback to management and policy	Indirect influence has not been tested separately
Income is a system outcome	EN1 receives an incoming score of 28 and EN2 receives 27	EN1 receives an incoming score of 28 and EN2 receives 27	Income emerges after various upstream conditions interact	No longitudinal analysis of costs, profits, taxation, or income distribution is available

Source: Focus group discussion results, MICMAC processing, field observation, and literature synthesis, 2025.

Internal validity cannot be established from the network order alone. The relationship between habitat and income can be influenced by market prices, nest quality, operating costs, harvest intensity, and marketing capacity; the relationship between weather and population can be influenced by factors outside the insect habitat distribution; the relationship between governance and outcomes can be influenced by implementer compliance and capacity. Causal testing requires measurement of mediators and confounders, temporal order, and variation between treatments and controls. Panel design, path models, or structural equations can be used after sample size, data distribution, and model identification are met.

External validity also needs to be limited. Bangka Belitung has an island configuration, mining history, hydrology, settlement density, and business governance that may not be identical to other swiftlet house locations in Indonesia or Southeast Asia. The habitat and weather positions can be plausible propositions in other regions, but matrix values, density, and institutional positions cannot be transferred without new assessment. Cross-regional comparison should use the same variable dictionary, comparable participant groups, separate matrices, and similar ecological protocols. In this way, similarities in mechanisms can be distinguished from local configuration specificities.

Reliability of field measurement further requires auditable quality control. Temperature and humidity sensors need to be given an identity, accuracy specifications, calibration records, installation time, position and elevation,

recording interval, and data download procedures. Insect traps must state the type of trap and the same bait unit; bird counts require consistent observation time; nest data must distinguish active nests, eggs, chicks, completed nests, and harvested nests. These standards enable biological change to be distinguished from changes in tools or procedures.

Testing P1 requires landscape measurements at several radii around the house because the distance of ecological response is not yet known. Predictors can include the percentage of water, wetlands, vegetation, agriculture, impervious surfaces, edge length, and connectivity. Intermediate responses are the number or biomass of aerial insects per unit effort, while biological responses include occupancy probability, intensity of entry-exit activity, number of active nests, and reproductive success. Multilevel models can separate between-house variation from seasonal variation.

Testing P2 needs to consider time lags. Rain can precede changes in larval habitat conditions, followed by insect emergence, changes in foraging activity, and reproductive responses. Distributed lag models or time-series models can compare weather influences at several horizons. Building microclimate can be placed as a mediator between external weather and nest responses, with building characteristics as effect modifiers.

Testing P3 requires observable governance indicators: registration completeness, monitoring frequency, availability of technical guidelines, location and noise compliance, pesticide management, habitat protection, harvest recording, and use of data in decisions. Interactions between these indicators and ecological exposure can show whether institutional capacity weakens the impact of fragmentation, extreme weather, or poor building management.

5. Limitations

The study has several limitations, namely first, a single consensus matrix does not capture differences between business actors, government, academics, and community. Second, individual score data are not available so inter-participant agreement measures cannot be calculated. Third, the complete matrix, numerical coordinates, and changes in direct–indirect influence rankings are not available for re-examination. Fourth, habitat and population are general constructs at the time of assessment; detailed ecological elements are only used to interpret mechanisms. Fifth, temperature–humidity readings are instantaneous and instrument metadata are incomplete. Sixth, insects, land cover, occupancy, reproduction, production, and harvest were not monitored longitudinally. These limitations apply primarily to the structural proposition-generating function, not to causal testing, coastal–urban comparison, or population sustainability estimation.

6. Conclusion

The MICMAC structure places habitat and weather upstream of the Bangka Belitung swiftlet house system. Habitat has the strongest outgoing influence, weather does not receive influence from other variables within the model boundary, and governance links ecological pressure with administrative and management responses. Swiftlet population and economic outcomes are located further downstream.

This finding answers the first objective at the level of stakeholder assessment structure. The second objective produces a habitat–prey–microclimate complementarity model: landscape and weather form foraging conditions and space; building microclimate filters nesting suitability; governance changes exposure and response capacity; while population and production follow downstream. Because these proximal variables have not been measured directly, the model can be tested through swiftlet house panels stratified by coastal–urban gradient and land cover for at least one annual cycle.

The practical implication is that policy cannot be focused only on building permits or economic revenue alone. Monitoring needs to start from changes in landscape and weather, insect and microclimate responses, then assess occupancy, reproduction, production, and harvest. Governance functions to link this evidence with location decisions, habitat protection, disturbance control, technical assistance, and adaptation. This sequence maintains sustainability as a testable biological and ecological condition, not a label derived from business growth.

Author Contributions

Conceptualization: H., M.S.S.A., S.B., I.M.F.; Methodology: H., I.M.F.; Formal analysis: I.M.F., H.; Investiga-

tion: H.; Data curation: H., I.M.F.; Writing—original draft preparation: H., I.M.F.; Writing—review and editing: I.M.F., H., R.; Supervision: I.M.F., M.S.S.A., S.B.; Validation: M.S.S.A., S.B., I.M.F.; Resources: H.; Project administration, H. All authors have read and agreed to the published version of the manuscript.

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The study protocol was reviewed and approved by the Ethics Committee of the Development Studies Program, Graduate School of Hasanuddin University, under ethics approval number 12718/UN4.1.27.21/PT.01.05/2023. The research was carried out according to the dissertation research guidelines from the University of Hasanuddin, Makassar, Indonesia.

Informed Consent Statement

Informed consent was obtained from all participants involved in the study.

Data Availability Statement

Data supporting the findings of this study are available from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, ChatGPT and Perplexity were used solely to assist with language refinement, structural clarity and figure generation. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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