RESEARCH ARTICLE

PERENNIAL PATHS: MAPPING ECOLOGICAL NETWORKS TO ENHANCE PREDATOR MOVEMENT AND PEST CONTROL IN COFFEE LANDSCAPES IN LIPA, BATANGAS

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Manuscript Info	*Abstract*
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	Perennial crop landscapes play a critical role in sustaining agricultural productivity, yet their ecological function is often weakened by habitat fragmentation that limits the movement of natural predators responsible for biological pest control. In the perennial-dominated landscape of Lipa City, Batangas, the primary challenge lies in improving predator connectivity between forest source habitats and crop feeding areas within an intensively managed agricultural matrix. This study employs a biotope-based ecological assessment and network modeling approach to address this issue through spatial planning. Using geographic information systems (GIS), the researcher generated a biotope map by integrating land cover, landform, soil, and watershed data, which served as the core spatial framework of the analysis. Each biotope was evaluated based on ecological criteria including area, rarity, habitat structure, and successional stage, allowing the classification of landscape units into creative, connective, integrative, and protective management strategies. Building on this assessment, an ecological network was constructed through predator source identification, perennial feeding target mapping, resistance surface modeling, and least cost path analysis. The resulting ecological network highlights functional corridors, connectivity gaps, and priority intervention zones where hedgerows, stepping stones, and buffer areas can enhance predator movement into perennial crops. Findings indicate that forested areas function as essential source habitats under protective management, while extensive perennial crop biotopes require integrative strategies to embed ecological function within production systems. Overall, the study demonstrates how combining biotope assessment with ecological network modeling can translate ecological analysis into actionable spatial strategies that strengthen biological pest control and support sustainable agricultural landscape planning.

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Introduction:-

Coffee remains one of the most economically and socially important perennial crops worldwide. In the Philippines, Kapeng Barako, a traditional Liberica-type coffee cultivated notably in Batangas, embodies both cultural heritage

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379 and agroecological challenges due to recurrent pest problems under intensive cultivation practices. Conventional pest-control methods often rely on synthetic insecticides and monoculture practices, which may deliver short-term yield but degrade biodiversity, weaken ecosystem resilience, and undermine sustainability. As global pressure on agricultural lands intensifies and climate change exacerbates environmental uncertainty, there is increasing interest in agroecological alternatives that harmonize crop production with ecosystem health. In particular, shaded or agroforestry-based coffee systems have been documented to support rich communities of birds, bats, predatory arthropods, and other beneficial organisms, natural enemies that provide essential ecosystem services, such as pest suppression, pollination, soil stabilization, and microclimate regulation (Perfecto et al. 2004; Vandermeer et al. 2010; Bertschinger & Perfecto 2013). Moreover, meta-analyses comparing shade-grown versus sun-grown coffee plantations have shown that farms with higher structural complexity (e.g. canopy cover, plant species diversity) harbour significantly greater biodiversity, especially among insects, which in turn may reduce reliance on chemical pesticides (Smith et al. 2024). Several studies also highlight that natural pest control, such as predation on pests like the Coffee Berry Borer (CBB), is more effective in coffee landscapes with ample tree cover and habitat diversity (Greenberg et al. 2000; Philpott et al. 2008; Jaramillo et al. 2009).

However, while many existing studies emphasize on-farm practices (shade trees, reduced pesticide use), fewer address the landscape spatial structure, that is, how the arrangement and connectivity of habitat patches, forest fragments, corridors, and other non-crop elements influence the movement and effectiveness of natural enemies across the broader agroecosystem. Yet evidence from landscape ecology and agroecosystem research suggests that such spatial configuration can substantially influence biological control services. For instance, a study of 16 coffee plantations in Brazil found that higher surrounding forest cover was strongly associated with increased abundance and richness of social wasps (natural enemies), as well as higher biocontrol of a major pest, more so than local farm management variables (Medeiros et al. 2019). Given this gap, this study pursues an integrative, landscape-scale approach in a real-world coffee region. The chosen study area lies in Lipa, Batangas, encompassing barangays such as Sto. Niño, Lumbang, and Marauoy. Using GIS- based spatial analysis, this research will produce a biotope map, an ecological assessment map, and an ecological network plan tailored to perennial coffee (Kapeng Barako) agroecosystems.

The aims of this study are to: (1) identify core habitat patches, forest fragments, and coffee parcels within the landscape; (2) design connectivity through ecological networks, including corridors, stepping stones, buffers, and hedgerows, to facilitate movement of natural enemies; (3) propose management prescriptions (e.g. shade-tree planting, hedgerows, predator perches) to bolster natural pest regulation; and (4) outline a monitoring framework to evaluate how spatial design influences pest incidence and biodiversity over time. By doing so, this research seeks to demonstrate how sustainable coffee production can coexist with ecological integrity. The framework of this study may offer a replicable model for coffee-producing regions in the Philippines and beyond, balancing agricultural productivity, biodiversity conservation, and long-term resilience in fragmented tropical landscapes.

Methodology:-
The study was conducted in coffee-producing landscapes in Lipa, Batangas, adjacent to the Malepunyo Range, encompassing the barangays of Sto. Niño, Lumbang, and Marauoy. Digital elevation model (DEM) data were acquired from publicly available sources, including EarthExplorer and Geoportal, to delineate watershed boundaries and derive hydrological features such as channel networks, ridgelines, and slopes. The watershed boundary defined the study area and served as the operative extent for subsequent spatial analyses in a GIS environment (QGIS). Foundational spatial layers were produced, including a landform map derived from slope and aspect analysis of the DEM, a landcover map based on satellite imagery and field verification identifying annual crops, perennial crops, built-up areas, and open forest, and a soil map confirming the dominance of Lipa Loam suitable for perennial and other crops. By overlaying and intersecting these layers, a biotope map was generated, where each unique combination of landform, landcover, and soil was considered a distinct biotope type.

The biotope map was subsequently evaluated using criteria adapted from Jarvis and Young (2005), considering rarity, habitat value, area, period of development, and stage of ecological succession. This evaluation facilitated the classification of the landscape into four functional ecological zones: creative, connective, integrative, and protective, resulting in an ecological assessment map that informed potential management strategies. The ecological network plan was developed using the assessment map as a foundation, with core habitat patches identified as forest remnants or large shade-coffee areas serving as reservoirs for natural enemies such as insectivorous birds, bats, and predatory arthropods. Connectivity was established through corridors and stepping-stone habitats to facilitate

movement of these organisms across coffee parcels, while buffer zones were delineated around sensitive areas such as riparian strips and steep slopes to maintain microclimate stability and provide refuge for beneficial fauna. Specific management prescriptions, including the planting of native shade trees, establishment of hedgerows, and installation of predator perches, were proposed to enhance natural pest control within perennial crop areas. The methodology was informed by a comprehensive desk-based literature review, integrating findings from global and regional studies on coffee agroecosystems, biodiversity, and biological pest control. Research on shade-grown coffee and agroforestry demonstrated that structurally complex plantations host greater abundance and richness of natural enemies, which reduce pest incidence and minimize the need for chemical interventions (Perfecto et al., 2004; Greenberg et al., 2000; Philpott et al., 2008; Jaramillo et al., 2009).

Landscape-scale studies indicated that forest cover and habitat connectivity influence the movement of predatory species, thereby enhancing ecosystem services in agricultural landscapes (Medeiros et al., 2019). Methodological frameworks from biotope mapping and landscape ecology were adapted to the coffee landscape context, emphasizing the integration of production and conservation objectives. Although the study relied on remote-sensed data and secondary sources for mapping, a proposed monitoring framework was designed to evaluate the effectiveness of the ecological network. The framework recommends regular surveys of predator presence, assessment of pest incidence in coffee parcels adjacent to network elements, and periodic updating of land cover and vegetation structure through remote sensing or ground-truthing. Adaptive management is envisioned, allowing adjustments to corridor widths, vegetation composition, and other management measures based on observed ecological outcomes. This approach demonstrates how landscape-scale ecological network planning can support biodiversity conservation while enhancing natural pest regulation in coffee agroecosystems.

Results and Discussion:-

This section presents the results and discussion of the biotope mapping, ecological assessment, and ecological network modeling undertaken in the study. The biotope map served as the foundational spatial dataset, providing the structural basis for identifying habitat types, predator source areas, movement barriers, and feeding zones within the agricultural landscape. Building on this, the ecological assessment map evaluated each biotope's condition and functional role using an ecological value matrix, allowing the researcher to classify management needs into creative, connective, integrative, or protective strategies. These assessments then informed the development of the ecological network map, which modeled predator movement through least-cost paths, resistance surfaces, and proposed hedgerow or stepping-stone interventions to address connectivity gaps. Together, these mapping outputs reveal how the existing biotope structure influences predator mobility and outline spatially explicit strategies to enhance natural pest control within perennial crop systems.
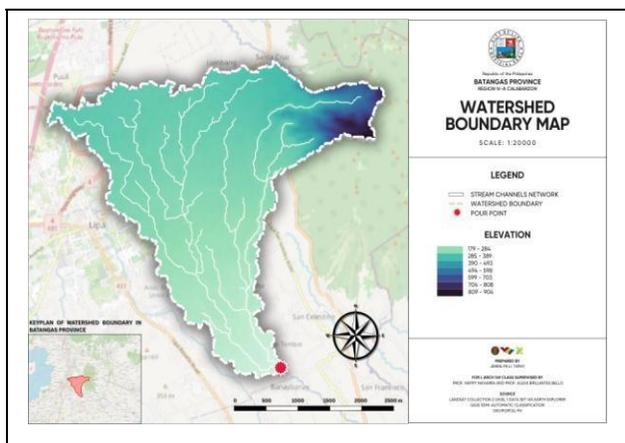
Biotope Mapping

Figure 1. Watershed Boundary

The results of the study begin with the biotope mapping process, which serves as the foundational spatial analysis from which all subsequent ecological assessments and network planning were derived. The biotope map was generated after delineating the watershed boundary of the study area located in Lipa City, Batangas, particularly

within the barangays of Sto. Niño, Lumbang, and Marauoy. The watershed boundary delineation was performed using Digital Elevation Model (DEM) data sourced from the Philippine Geoportal and cross-verified with elevation datasets from the United States Geological Survey's EarthExplorer. The delineation process not only defined the extent of the study area but also established the drainage patterns and channel networks that influence ecological flows and land suitability within the site. Following boundary delineation, three preliminary thematic maps, landcover, landform, and soil, were constructed to capture the existing environmental conditions shaping each biotope type.
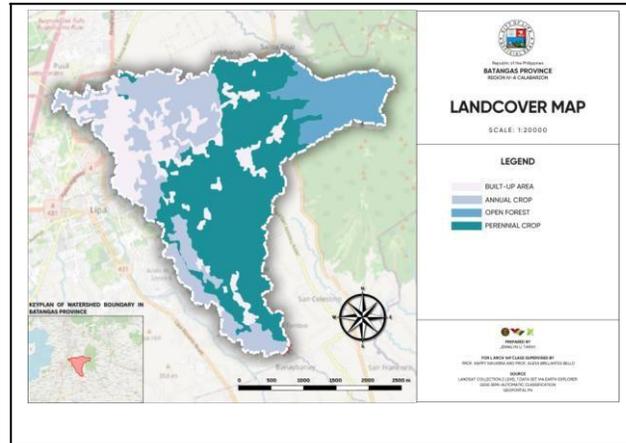

Figure 2. Landcover Map

The landcover map (figure 2) was developed using classified satellite data, further refined through visual verification with publicly available aerial imagery. Four landcover classes were identified: built-up areas, annual crops, perennial crops, and open forest. These categories reflect the predominant land uses in Lipa Batangas, where agriculture remains a central component of the local landscape. Consistent with local agricultural profiles, the map revealed that perennial crops occupy the largest proportion of the study area, followed by annual crops. The perennial crop category includes coffee (particularly Liberica or kapeng barako), fruit-bearing trees, and mixed agroforestry vegetation typically found in Lipa's upland barangays. Built-up areas appear sparsely and are concentrated along the western portion of the map, corresponding to the more urbanized sectors closer to the city proper. Meanwhile, the eastern side of the study area, adjacent to the slopes of Mount Malepunyo, is characterized by open forest cover, indicating the presence of secondary growth and dense vegetation associated with the mountain range. This spatial distribution highlights a strong gradient from agricultural lowlands to forested uplands, which is ecologically relevant given the site's potential for predator movement and habitat connectivity.
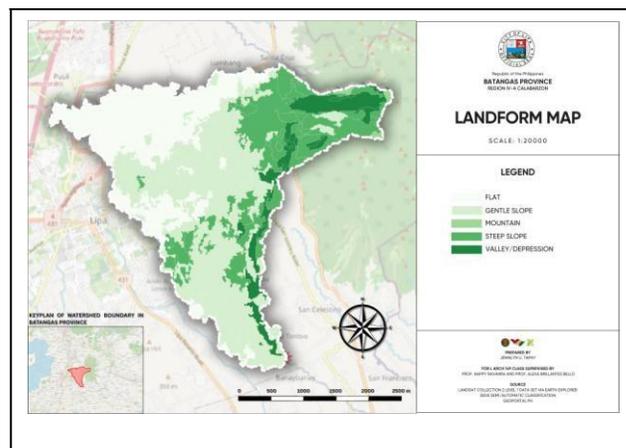

Figure 3. Landform Map

The landform map (figure 3) further clarified the physical structure of the landscape. Five landform types were identified: flat, gentle slope, steep slope, mountainous terrain, and valley or depression. The majority of the study area is composed of flat to gently sloping landforms, which align with the extensive presence of agricultural land uses. The easternmost section, where Mount Malepunyo is situated, exhibits predominantly steep slopes, rugged mountainous terrain, and isolated valley formations. These geomorphic conditions influence accessibility, vegetation type, soil retention, and the potential establishment of ecological corridors. Steeper areas, while less suitable for intensive agriculture, serve as important habitat refugia for wildlife and can host natural predators of crop pests—an important consideration for designing an ecological network aimed at pest regulation. The third preliminary layer, the soil map (figure 4) , revealed that the entire study area is covered by a single soil type: Lipa Clay Loam.

According to the Bureau of Soils and Water Management, Lipa Clay Loam is highly suitable for a wide range of agricultural crops, including annuals, perennials, and tree crops such as Liberica coffee. Its texture and nutrient profile support deep-rooting vegetation and provide favorable conditions for long-term perennial agriculture. The uniformity of soil type across the study area contributes to consistent crop growth conditions but also implies that differences in vegetation patterns are largely driven by landform, microclimate, and land management practices rather than soil variability alone. By overlaying landcover, landform, and soil datasets through GIS intersection, the researcher generated the biotope map (figure 5), which captures unique combinations of these environmental attributes. To improve analytical tractability, biotope polygons smaller than 5 hectares were merged with adjacent, dominant biotope units, resulting in a final map composed of 14 distinct biotope types and 136 biotope units. Each biotope type was assigned a unique code based on standard naming conventions to facilitate classification and ecological assessment (Table 1)
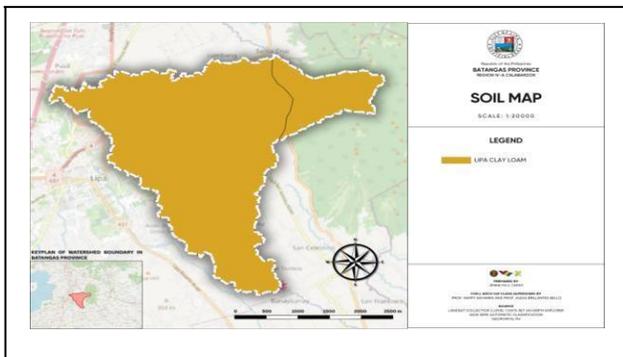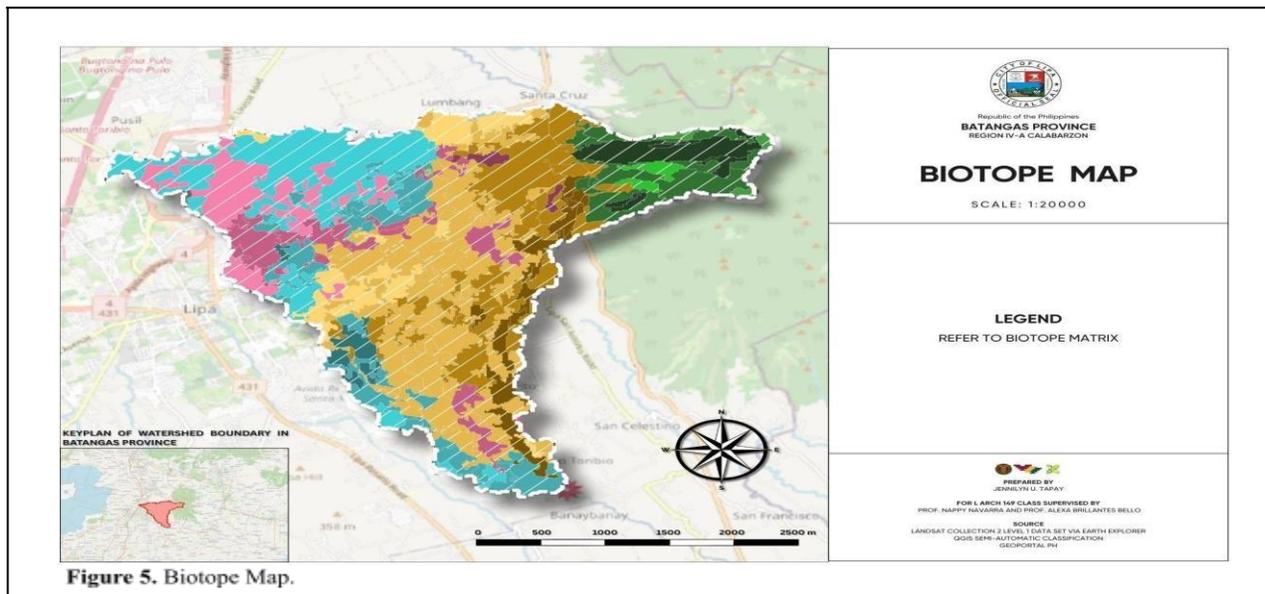

Figure 4. Soil Map

Figure 5. Biotope Map.

The spatial distribution of biotope types showed a landscape dominated by perennial crop biotopes, followed by annual crop and open forest biotopes, with built-up areas occupying the smallest proportion. The dominance of perennial crop biotopes validates the relevance of the current study's focus on ecological strategies to enhance predator movement and manage pest dynamics within coffee-dominated agroecosystems. The juxtaposition of extensive agricultural land uses with remnant forest patches provides a compelling context for ecological network planning, as landscape heterogeneity has been shown to influence the abundance and movement of natural enemies that contribute to biological pest control (Tscharntke et al., 2005). Following biotope delineation, the researcher conducted an ecological evaluation to determine the relative ecological value and management priorities of each biotope type. This evaluation informed the classification of biotope units into functional ecological zones, setting the stage for detailed assessment mapping and ecological network design. These subsequent analyses aim to address gaps in habitat connectivity and pest-regulator dynamics identified through the biotope mapping process.

Assessment Mapping:-
The ecological assessment of biotope units was conducted to determine their relative ecological value and management priorities. This assessment framework was adapted from Jarvis and Young's (2005) The Mapping of Urban Habitat and Its Evaluation (2005), which provides standardized criteria for evaluating habitat characteristics relevant to ecological planning. The criteria applied to each biotope type included area, rarity, period of development, habitat complexity, and stage of ecological succession.
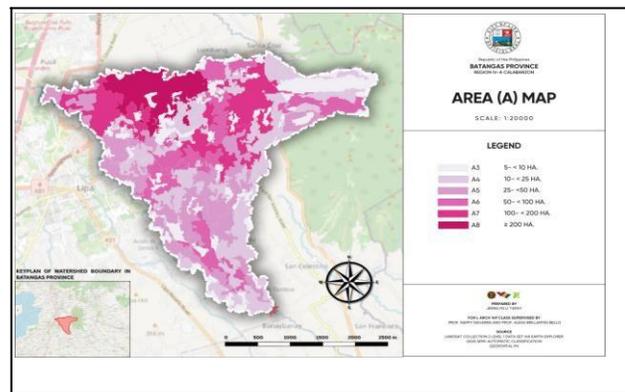
Figure 6. Area Map

The area assessment evaluated the spatial extent of each biotope, categorizing them from A3 to A8 based on standardized size thresholds. Biotopes ranging from 5 to <10 hectares were classified as A3, while those >200 hectares were designated A8. The results indicate that most biotope units fall below 40 hectares, reflecting the fragmented nature of agricultural landscapes in Lipa City. The largest biotope category corresponded to annual crop areas, which exceeded 50 hectares in some portions of the study area. Area size directly influences ecological stability, species richness, and potential for predator movement, with larger patches generally supporting more robust ecological processes (Forman, 1995).
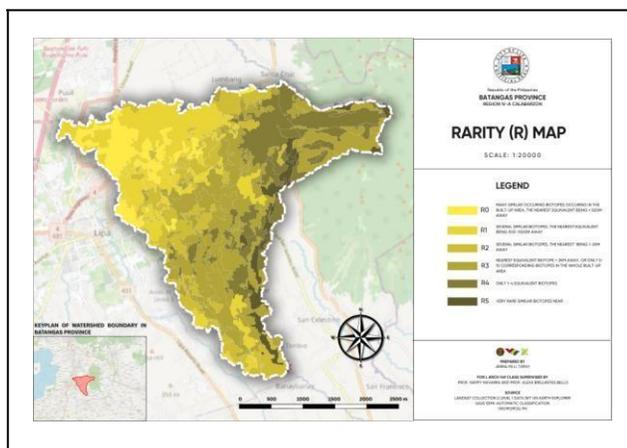
Figure 7. Rarity Map
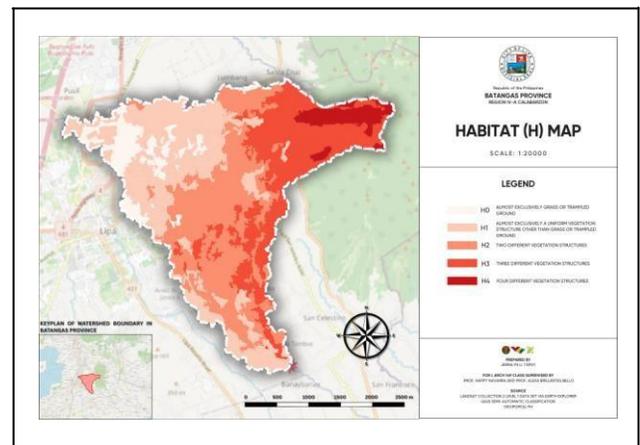
Figure 9. Habitat Map

The rarity assessment examined the proximity and frequency of similar biotope types within the landscape. Categories ranged from R0, characterized by numerous similar biotopes within <500 meters, to R5, which indicates highly rare or isolated biotopes. The analysis showed that built-up and annual crop biotopes scored lower on rarity (R0–R1) due to their prevalence and spatial clustering. In contrast, perennial crop biotopes and forest biotopes registered higher rarity values (R3–R5), suggesting greater ecological uniqueness and reduced redundancy within the landscape matrix. Rarer habitats often contribute disproportionate ecological value and may serve as critical nodes for biodiversity conservation (Hunter, 1996).

Figure 8. Period of Development Map.

Figure 10. Stage of Ecological Succession Map

The period of development assessment evaluated the estimated time required for each biotope type to develop if recreated elsewhere. Categories ranged from PD0 (1–2 years) to PD5 (>100 years). Most biotopes in the study area scored PD2 to PD4, indicating development periods ranging from 5 to more than 50 years. Perennial crop s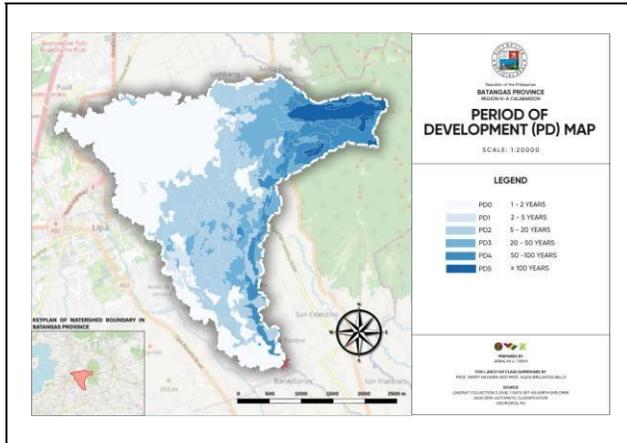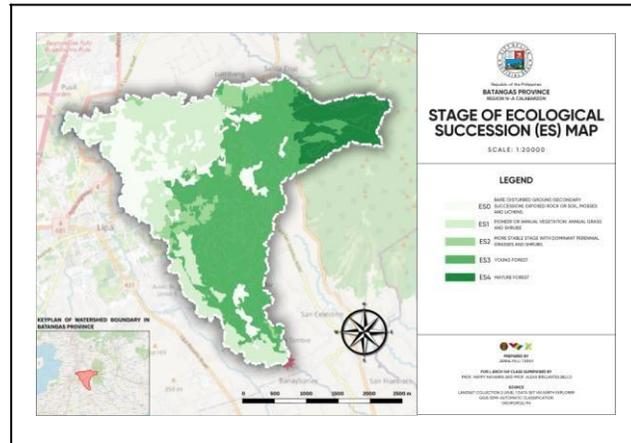ystems and forest biotopes predictably exhibited longer development periods, consistent with the growth cycles of tree crops and natural forest succession. This metric underscores the ecological investment embedded in long-established biotopes, which contributes to habitat stability and the persistence of natural enemies relevant to pest control (Perfecto & Vandermeer, 2008). The habitat assessment evaluated vegetation structure and species composition across biotope units. Habitat categories ranged from H0, representing bare or trampled ground, to H4, representing areas with four or more distinct vegetation layers. The results show that annual and perennial crop biotopes commonly fall under H2 or H3, reflecting moderate vegetation diversity arising from crop–understory–canopy interactions.

Forest biotopes exhibit the highest habitat complexity (H4), characterized by stratified vegetation layers. Built-up biotopes correspondingly fell into H0 due to limited vegetation and prevalence of impervious surfaces. Habitat complexity is a critical predictor of predator presence, as structurally diverse environments facilitate refuge, foraging, and movement (Landis et al., 2000). The final criterion, ecological succession, assessed the maturity of each biotope based on its position within the successional continuum. Categories ranged from ES0 (bare or disturbed ground) to ES4 (mature forest). Annual crops predominantly fell under ES1, representing pioneer vegetation dominated by short-lived plant species. Perennial crop biotopes were categorized under ES2 and ES3, indicating more stable communities dominated by longer-lived plants, shrubs, or young trees. The forested section near Mount Malepunyo was classified as ES4, denoting mature forest conditions with complex ecological processes. Successional stage is directly related to ecosystem stability and capacity for sustaining predator populations essential for natural pest control (Bianchi et al., 2006). Collectively, these assessments reveal a landscape characterized by extensive perennial crop biotopes with moderate habitat complexity and mid-successional stages. These conditions highlight both the ecological potential and current limitations for sustaining natural predators in coffee-dominated agricultural systems. The assessment results inform the succeeding ecological network planning, which aims to strengthen habitat connectivity and enhance the movement of key predator species across the landscape.

ECOLOGICAL ASSESSMENT
FOR BATANGAS PROVINCE, REGION IV-A, CALABARZON

VALUE ASSESSMENT MATRIX

Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Numeric Equivalent
	R0	PD0	H0	ES01	1
	R1	PD1	H1	ES1	2
	R2	PD2	H2	ES2	3
A3	R3	PD3	H3	ES3	4
A4	R4	PD4	H4	ES4	5
A5	R5	PD5			6
A6					7
A7					8
A8					9

ECOLOGICAL VALUE MATRIX

Numeric Equivalent (Range)	Management
1 - 8	Creative Management
9 - 16	Connective Management
17- 24	Integrative Management
25 - 30	Protective Management

Table 2&3. Value Assessment Matrix and Ecological Value Matrix

ECOLOGICAL ASSESSMENT
FOR BATANGAS PROVINCE, REGION IV-A, CALABARZON

VALUE ASSESSMENT MATRIX

Biotope	Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Ecological Value (Total)	Management Type
LACGS	A4	R2	PD0	H1	ES1	13	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A4	R2	PD0	H1	ES1	13	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A5	R2	PD0	H1	ES1	14	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A4	R2	PD0	H1	ES1	13	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A3	R2	PD0	H1	ES1	12	Connective Management
LACGS	A4	R2	PD0	H1	ES1	13	Connective Management
LACSS	A3	R3	PD1	H2		15	
LACSS	A5	R3	PD1	H2	ES1	17	
LBAGS	A3	R1	PD0	H1	ES0	10	Connective Management
LBAGS	A3	R1	PD0	H1	ES0	10	Connective Management
LBAGS	A4	R1	PD0	H1	ES0	11	Connective Management
LBAGS	A5	R1	PD0	H1	ES0	12	Connective Management
LBAGS	A4	R1	PD0	H1	ES0	11	Connective Management
LBASS	A4	R2	PD1	H1	ES0	13	Connective Management
LBASS	A3	R2	PD1	H1	ES0	12	Connective Management
LOFGS	A4	R4	PD4	H3	ES3	23	Integrative Management
LOFGS	A4	R4	PD4	H3	ES3	23	Integrative Management
LOFMS	A3	R5	PD5	H4	ES4	26	Protective Management
LOFMS	A3	R5	PD5	H4	ES4	26	Protective Management
LOFMS	A3	R5	PD5	H4	ES4	26	Protective Management
LOFSS	A4	R3	PD4	H3	ES4	23	Integrative Management
LOFSS	A4	R3	PD4	H3	ES4	23	Integrative Management
LOFSS	A4	R3	PD4	H3	ES4	23	Integrative Management
LOFSS	A3	R3	PD4	H3	ES4	22	Integrative Management
LOFSS	A4	R3	PD4	H3	ES4	23	Integrative Management
LOFSS	A6	R3	PD4	H3	ES4	25	Protective Management
LOFSS	A5	R3	PD4	H3	ES4	24	Integrative Management
LOFV	A3	R4	PD5	H4	ES4	25	Protective Management
LOFV	A3	R4	PD5	H4	ES4	25	Protective Management
LOFV	A4	R4	PD5	H4	ES4	26	Protective Management
LOFV	A3	R4	PD5	H4	ES4	25	Protective Management
LOFV	A3	R4	PD5	H4	ES4	25	Protective Management
LPCF	A6	R2	PD2	H2	ES2	19	Integrative Management
LPCF	A3	R2	PD2	H2	ES2	16	Connective Management
LPCF	A3	R2	PD2	H2	ES2	16	Connective Management
LPCF	A4	R2	PD2	H2	ES2	17	Integrative Management
LPCF	A6	R2	PD2	H2	ES2	19	Integrative Management
LPCF	A3	R2	PD2	H2	ES2	16	Connective Management
LPCF	A3	R2	PD2	H2	ES2	16	Connective Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management

Table 4. Biotope Assessment

ECOLOGICAL ASSESSMENT
FOR BATANGAS PROVINCE, REGION IV-A, CALABARZON

VALUE ASSESSMENT MATRIX

Biotope	Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Ecological Value (Total)	Management Type
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A6	R3	PD2	H2	ES3	21	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A6	R3	PD2	H2	ES3	21	Integrative Management
LPCGS	A7	R3	PD2	H2	ES3	22	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A5	R3	PD2	H2	ES3	20	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management

ECOLOGICAL ASSESSMENT
FOR BATANGAS PROVINCE, REGION IV-A, CALABARZON

VALUE ASSESSMENT MATRIX

Biotope	Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Ecological Value (Total)	Management Type
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A3	R4	PD3	H3	ES3	21	Integrative Management
LPCSS	A5	R4	PD3	H3	ES3	23	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A3	R4	PD3	H3	ES3	21	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A5	R4	PD3	H3	ES3	23	Integrative Management
LPCSS	A3	R4	PD3	H3	ES3	21	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management

Biotope	Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Ecological Value (Total)	Management Type
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A5	R3	PD2	H2	ES3	20	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A5	R3	PD2	H2	ES3	20	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A5	R3	PD2	H2	ES3	20	Integrative Management
LPCGS	A3	R3	PD2	H2	ES3	18	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCGS	A6	R3	PD2	H2	ES3	21	Integrative Management
LPCGS	A5	R3	PD2	H2	ES3	20	Integrative Management
LPCGS	A4	R3	PD2	H2	ES3	19	Integrative Management
LPCSS	A4	R4	PD3	H3	ES3	22	Integrative Management
LPCSS	A7	R4	PD3	H3	ES3	25	Protective Management

Biotope	Area (A)	Rarity (R)	Period of Development (PD)	Habitat (H)	Stage of Ecological Succession (ES)	Ecological Value (Total)	Management Type
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management
LPCV	A3	R5	PD4	H3	ES3	23	Integrative Management
LPCV	A3	R5	PD4	H3	ES3	23	Integrative Management
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management
LPCV	A4	R5	PD4	H3	ES3	24	Integrative Management
LPCV	A5	R5	PD4	H3	ES3	25	Protective Management
LPCV	A3	R5	PD4	H3	ES3	23	Integrative Management

Figure 11. Ecological Management Map.

After the ecological value assessment was completed, the researcher synthesized the results into an Ecological Management Map, which spatially illustrates the distribution of recommended management strategies across the study area(Figure 11).The map indicates that built up areas and annual crop biotopes are predominantly classified un der connective management, reflecting their limited ecological value yet strategic importance in maintaining landscape connectivity. Small and scattered patches within annual croplands were assigned creative management, highlighting opportunities for habitat creation in degraded or underutilized spaces. The extensive perennial crop biotopes dominating the site were categorized under integrative management, emphasizing the need to embed ecological functions within productive agricultural areas to enhance predator movement and pest regulation. In contrast, the forested zones of the Mount Malepunyo range were classified under protective management due to their mature ecological condition and role as critical source habitats. Creative management focuses on introducing ecological functions in areas with low habitat quality, such as disturbed plots and marginal sections of annual cropland.

These areas typically lack the structural diversity necessary to support natural predators; therefore, interventions such as native shrub planting, flower-rich vegetation, and small microhabitats are recommended. By increasing vegetation complexity, these spaces can begin to support insects, birds, and ground-dwelling arthropods, allowing them to function as supplementary refuges and stepping areas within the broader ecological network. In connective management zones, the primary objective is to enhance ecological permeability between larger habitat patches. Vegetated corridors, including hedgerows, grass strips, and riparian buffers, are proposed to facilitate predator movement across fragmented landscapes. These linear elements enable the dispersal of insectivorous birds, bats, and beneficial insects by reducing exposure and energetic costs during movement. When combined with reduced pesticide use and the installation of perches or roosting structures, connective strategies strengthen functional links between forested source habitats and perennial crop areas. Integrative management, applied mainly to perennial crop biotopes, aims to incorporate ecological processes directly into agricultural production.

Enhancing habitat heterogeneity through intra-farm corridors, understory vegetation, and hedgerows supports predator presence while maintaining crop productivity. Measures such as controlled understory growth, selective pesticide application, and the provision of bat boxes or raptor perches improve predator effectiveness and promote sustained biological pest control within perennial systems. Finally, protective management applies to ecologically significant forest areas near the Mount Malepunyo range, which serve as primary nesting and refuge habitats for natural predators. Conservation-oriented strategies, including strict land-use protection, buffer zone maintenance, and the prevention of chemical drift from adjacent farms, are essential to preserving these source habitats. Maintaining forest integrity ensures the continued supply of predators to surrounding agricultural landscapes, reinforcing the long-term sustainability of ecological pest control mechanisms.

Ecological Networking:-
To translate the ecological assessment into a functional spatial strategy, a series of network construction maps was developed to model predator movement within the perennial crop landscape. These maps were produced sequentially to identify the key ecological nodes, the movement constraints imposed by landcover, and the most probable routes connecting predator source habitats to feeding areas within perennial crops. Together, they form the analytical foundation for the ecological network by clarifying where predators originate, how they navigate the landscape, and which areas require targeted intervention to enhance biological pest control.
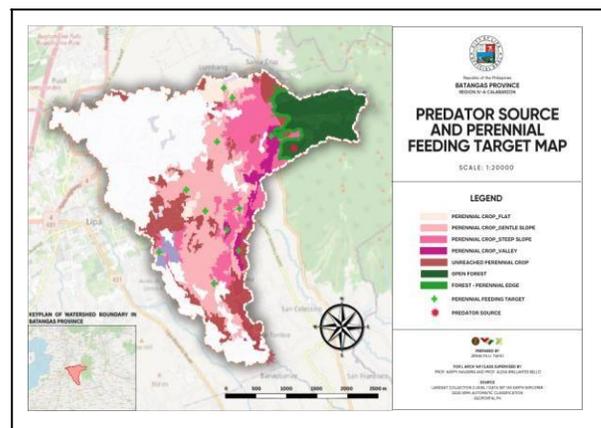

Figure 12. Predator Source and Perennial Feeding Target Map

The first network construction map (figure 12) identifies the ecological endpoints that structure predator movement: the source habitats and the feeding targets. Forest edges and dense semi-natural patches in the Mount Malepunyo sector were mapped as predator source areas, representing likely nesting and roosting habitats for insectivorous birds such as tailorbirds, shrikes, Philippine bulbuls, and pied fantails, which are known predators of caterpillars, beetles, and scale insects commonly affecting perennial crops (Gaston et al., 2021; Whelan et al., 2015). Adjacent shade coffee or mixed-tree perennial systems also serve as secondary predator reservoirs. Feeding targets were then identified along the edges of perennial crop polygons, where arthropods accumulate and where avian and arthropod predators commonly forage due to increased prey density and structural accessibility (Mata et al., 2017). By mapping both node types, source and feeding points, the study establishes the spatial origin and destination of predator movement, forming the basis for subsequent least-cost analysis.
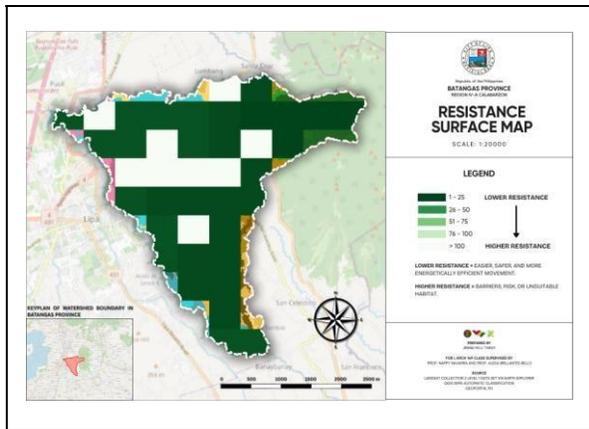

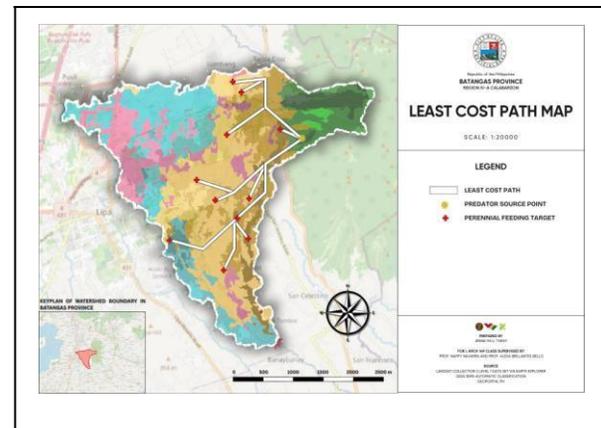**Figure 13.** Resistance Map.

Figure 14. Least Cost Path Map

The second network construction map (figure 13) represents the resistance surface, which models the relative difficulty predators experience when moving across the landscape. Resistance values were assigned according to landcover characteristics influencing movement or exposure risk. Forest and hedgerow vegetation were assigned the lowest resistance due to continuous canopy cover that facilitates movement and reduces predation risk for insectivorous birds and ground-active predators (Prevedello & Vieira, 2010). Perennial crops exhibit moderate resistance because they remain structurally permeable but are less sheltered than forest. Annual crops, grasslands, and bare open areas were given high resistance values as these habitats expose small predators to heat stress, competition, and aerial threats. Built-up areas were assigned near-prohibitive cost due to hard surfaces and intensive human disturbance, which substantially deter bird and arthropod movement (Soh et al., 2016). By clipping the resistance raster to the 100-m perennial buffer, the surface focuses the modeling on the ecological zone most relevant to pest control in perennial agriculture. The third network construction map (figure 14) displays least-cost paths (LCPs) generated from the resistance model between forest source nodes and perennial feeding targets. These LCPs highlight the most energetically efficient and behaviourally realistic routes through which predators are expected to move from their nesting habitats into crop fields.

The resulting linear paths were buffered to approximately 100 m to convert the theoretical lines into functional ecological corridors capable of supporting movement of different predator guilds, including birds, bats, ants, spiders, and predatory beetles—taxa known to contribute substantially to suppressing scale insects, mealybugs, and coffee berry borer in perennial systems (Maas et al., 2016; Karp et al., 2018). These buffered corridors reveal the areas where natural pest suppression is likely to be strong, where movement bottlenecks occur, and where intervention will be necessary to enhance connectivity. The Ecological Network Mapping (figure 15) subsection synthesizes the biotope classification, ecological assessment, and network construction analyses into a spatially explicit management framework that directly addresses the study's central issue: the limited and uneven movement of natural predators into perennial crop areas. By integrating predator source habitats (open forest and forest–perennial edges), perennial feeding targets, resistance surfaces, least-cost paths, and proposed hedgerow habitats, the researcher produced an ecological network map that visualizes how biological pest control services can be strengthened across the landscape. Rather than treating perennial croplands as isolated production units, the map

reframes them as part of a connected ecological system influenced by forest proximity, land-cover permeability, and targeted green infrastructure. The resulting network demonstrates a clear source–corridor–target strategy. Forest areas within the Mount Malepunyo range function as primary predator reservoirs, supplying insectivorous birds, bats, and arthropods that disperse outward into adjacent agricultural land. Least-cost path corridors radiating from these forest edges toward perennial crop zones indicate the most energetically and behaviorally feasible movement routes for predators, particularly through areas classified under integrative and connective management. These corridors intentionally follow perennial crop valleys, gentle slopes, and structurally complex land covers, where resistance is lower and habitat continuity can be realistically maintained. By buffering these paths, the researcher translated abstract movement lines into spatially implementable corridor zones that can support sustained predator movement rather than sporadic incursions. A critical outcome of the network analysis is the identification of unreached perennial crop patches, which appear prominently in the southern and interior sections of the site.

These areas represent ecological gaps where perennial crops remain disconnected from forest-derived predator flows due to surrounding high-resistance land uses or insufficient vegetation structure. To address this, the researcher strategically introduced hedgerow habitats and stepping-stone elements, shown as linear and clustered green features, to bridge these gaps. These interventions are deliberately modest in scale, aligning with creative and connective management principles, and are intended to incrementally improve landscape permeability without requiring large-scale land-use conversion. This approach prioritizes feasibility while maximizing ecological gain by linking isolated crop areas to the broader predator network. Overall, the final ecological network map operationalizes the ecological assessment by explicitly showing where protection must be maintained, where connectivity must be reinforced, and where new habitat must be created or integrated. It provides a spatial justification for targeted management actions, such as hedgerow establishment, buffer enhancement, and corridor protection—based on modeled predator movement rather than generalized assumptions. In doing so, the map serves not only as a visualization of ecological connectivity but as a decision-support tool that aligns landscape planning with biological pest control objectives. Through this integrative strategy, the ecological network strengthens the functional relationship between forest ecosystems and perennial agriculture, supporting more resilient and ecologically driven pest management across the study area.

Conclusion:-

This study demonstrated how biotope mapping, ecological assessment, and network-based spatial analysis can be integrated to address the limited movement of natural predators within perennial agricultural landscapes in Lipa, Batangas. By classifying land-cover types into functional biotopes and evaluating their ecological roles, the researcher was able to identify critical gaps in habitat connectivity that constrain biological pest control. The results highlight that while forest areas within the Mount Malepunyo range remain ecologically intact and function as key predator sources, much of the surrounding perennial cropland requires targeted interventions to enhance predator access and movement. Through ecological assessment and network construction, the study translated ecological potential into actionable spatial strategies. Least-cost path modeling revealed priority corridors linking forest habitats to perennial feeding areas, while resistance mapping clarified which land-cover types facilitate or impede predator movement.

The identification of unreached perennial patches underscored the need for complementary measures such as hedgerows, stepping-stone habitats, and buffer enhancements. Together, these strategies emphasize integrative and connective management approaches that embed ecological function within productive landscapes rather than separating conservation from agriculture. Overall, the ecological network map provides a spatially explicit planning framework that supports sustainable pest management through enhanced landscape connectivity. By strengthening linkages between forest source habitats and perennial crop systems, the proposed network promotes the long-term persistence of natural predator populations and their associated ecosystem services. This approach offers a replicable model for agroecological planning in similar tropical agricultural contexts, demonstrating how spatial analysis can inform landscape-scale interventions that balance productivity, biodiversity conservation, and ecological resilience.

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