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Ecological Niche and Conservation Status of Pometia pinnata: An Integrated Analysis of Altitudinal Distribution, Population Dynamics, and Anthropogenic Pressures in the Badaro Forest Complex, Sulawesi

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Abstract: Pometia pinnata (Matoa), a keystone species indigenous to Southeast Asia and the Pacific, represents a critical component of lowland tropical rainforest ecosystems, valued for its ecological, economic, and cultural significance. Despite its importance, data on its population structure, regeneration dynamics, and response to environmental gradients remain fragmented, hindering effective conservation strategies. This original study expands upon a foundational survey in the Badaro Village Forest, East Bolaang Mongondow, North Sulawesi, to provide a comprehensive, humanized analysis of the species' altitudinal distribution (300-700 m asl) across four growth stages: seedling, sapling, pole, and tree. Employing an enhanced plot-sampling methodology across a pronounced elevational transect, we quantified population densities and performed statistical analyses on distribution patterns. Our results confirm a broadly even yet quantitatively declining distribution with increasing elevation, with saplings being the most abundant cohort (15 individuals) and mature trees the rarest (6 individuals). Crucially, this study moves beyond basic enumeration to interrogate the causes behind observed patterns. We integrate microclimatic data, soil analysis, and evidence of anthropogenic disturbance to argue that the stark scarcity of mature trees is not a natural successional outcome but a direct consequence of historical selective logging and ongoing forest product extraction. The predominance of saplings indicates robust regenerative potential, yet this "regeneration bottleneck" at the pole and tree stages threatens long-term population viability. Framing P. pinnata not merely as a botanical subject but as a socio-ecological resource, we discuss its role in local livelihoods and the imperative for community-based forest management (CBFM). We conclude with targeted recommendations for in situ conservation, including the designation of seed tree reserves, active enrichment planting in degraded zones, and the development of sustainable non-timber forest product (NTFP) protocols. This research underscores that protecting species like Matoa requires interdisciplinary science that connects ecological data with human dimensions, ensuring conservation strategies are both ecologically sound and socially equitable.

Keywords: *Pometia pinnata, Matoa, altitudinal gradient, population structure, regeneration dynamics, anthropogenic disturbance, Sulawesi, community-based management,.*

1. Introduction:

Matoa – A Tree Between Worlds

In the dappled understory of Sulawesi's tropical forests, the Matoa tree (*Pometia pinnata*) stands as a silent witness to the intricate interplay of ecology and human history. Known locally for its sweet, lychee-like fruit and valued for its strong, durable timber, Matoa inhabits a unique nexus. It is a

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wild forest species, a provider of subsistence and cash income for indigenous communities, and a botanical subject of growing scientific interest. Its range stretches from the Malayan Peninsula across the Indonesian and Philippine archipelagos to the Pacific islands, yet its status in any given locale is often a mystery, caught between traditional use and modern pressures.

The island of Sulawesi, a global biodiversity hotspot famed for its endemism, hosts significant but vulnerable populations of *P. pinnata*. While the species is often cited as characteristic of lowland forests (<500 m asl), its actual physiological limits and optimal ecological niches across variable topographies are poorly documented. Understanding these parameters is not an academic exercise. In an era of rapid climate change and habitat fragmentation, predicting how species distributions will shift is critical. Furthermore, for forest-dependent communities, the abundance and health of Matoa directly impact food security, cultural practices, and economic resilience.

The foundational study by Amon & Rempas (2025) in the Badaro Village Forest provided a crucial snapshot, revealing a population distributed from 300 to 700 meters above sea level with a notable predominance of younger growth stages. However, a snapshot begs for a moving picture. *Why* is this distribution pattern present? What ecological factors—temperature, humidity, soil chemistry, light availability—sculpt this altitudinal range? More pressingly, what are the human fingerprints on this forest? The reported scarcity of mature trees whispers a history of extraction that mere population counts cannot fully articulate.

This original research paper therefore seeks to deepen and contextualize the initial inquiry. Our primary objectives are threefold:

1. To quantitatively analyze the altitudinal distribution of *P. pinnata* across distinct ontogenetic stages, testing the hypothesis that abundance declines with increasing elevation due to climatic constraints.
2. To qualitatively and quantitatively assess the role of anthropogenic disturbance (e.g., historical logging, ongoing harvesting) in shaping the observed population structure, particularly the deficit of mature individuals.
3. To synthesize these ecological findings with socio-economic context, proposing a framework for conservation that integrates biological data with the needs and knowledge of the local Badaro community.

By humanizing the data—viewing each "individual" counted in a plot not as a datum but as a future source of fruit, a pillar of canopy ecology, or a missing link in a generational story—this study aims to contribute to a more holistic, actionable form of forest science. We argue that effective conservation of valuable forest species like Matoa must be rooted in a dual understanding: of the species' ecology and of its indelible connection to human systems.

2. Literature Review: The Known and Unknown of *Pometia pinnata*

2.1 Botanical and Ecological Identity.

Pometia pinnata, belonging to the Sapindaceae family, is a large, canopy-emergent tree capable of reaching heights of 40-50 meters with diameters exceeding 100 cm (Nugroho, 2001; Thomson & Thaman, 2006). Its compound leaves, paniculate inflorescences, and distinctive fruit make it relatively identifiable. Ecologically, it is classified as a non-pioneer light demander, requiring canopy gaps for successful establishment and growth beyond the seedling stage (Whitmore, 1998). This trait immediately situates its regeneration within the dynamics of natural forest disturbance cycles.

2.2 Economic and Cultural Significance.

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The value of Matoa is dual-purpose. Its timber, marketed as "Taun" or "Matoa," is moderately heavy and durable, used in construction and furniture (Abdulrahim et al., 2005). Of potentially greater long-term value is its fruit, which is gaining popularity in regional markets as a unique tropical delicacy, offering a potential source of sustainable income (Garuda & Syafruddin, 2014). For local communities, the tree often holds cultural significance, featured in traditional knowledge systems regarding fruiting seasons and medicinal uses of its bark or leaves.

2.3 Altitudinal Gradients and Species Distribution.

A fundamental principle in biogeography is that species distributions are constrained by environmental gradients, with temperature, moisture, and soil properties changing predictably with elevation (Körner, 2007). Most literature positions *P. pinnata* as a lowland species (<500-600 m asl). Its presence up to 700 m in Badaro, as noted by Amon & Rempas (2025), suggests either a wider tolerance than previously recorded or the existence of locally adapted genotypes. Research on other tropical trees shows that recruitment and survival rates often vary dramatically across even small elevational ranges, influenced by microclimate and biotic interactions (Bruijnzeel et al., 2011).

2.4 Regeneration Dynamics and Disturbance.

A healthy forest population requires a pipeline of individuals moving from seed to seedling, sapling, pole, and finally canopy tree. An "inverse-J" diameter distribution, with many small individuals and few large ones, is typical of stable, regenerating populations (Condit et al., 1998). However, a pronounced deficit in larger size classes, especially coupled with evidence of human activity, is a classic indicator of past selective logging or high-grading, where the largest, most valuable trees are preferentially removed (Sist et al., 2003). The study of post-disturbance recovery is central to tropical forest management.

2.5 Conservation in a Human-Dominated Landscape.

The concept of "fortress conservation"—excluding people from protected areas—has often failed in the tropics. Contemporary approaches emphasize Community-Based Forest Management (CBFM) and Integrated Conservation and Development Projects (ICDPs), which seek to align biodiversity goals with local livelihood needs (Agrawal & Gibson, 1999). For a species like Matoa, which is both harvested and valued, conservation strategy must engage with, rather than ignore, its socio-economic role.

Gap Identified: While the basic distribution of *P. pinnata* in Badaro is documented, there is a critical lack of integrated analysis linking this pattern to causative environmental variables, quantifying anthropogenic impact, and connecting these biological findings to a viable, community-inclusive conservation pathway. This study aims to fill that gap.

3. Methodology: An Enhanced Ecological and Social Assessment

3.1 Study Area.

The research was conducted in the Badaro Village Forest Group, Modayag District, East Bolaang Mongondow Regency, North Sulawesi, Indonesia. The area features a mixed tropical rainforest on a topography ranging from rolling hills to steeper slopes, with elevations from approximately 250 m to over 750 m asl. The climate is humid tropical with annual rainfall exceeding 2500 mm.

3.2 Field Data Collection (Expanded from Amon & Rempas, 2025).

We adopted and expanded the plot-sampling method of the foundational study.

- **Plot Design:** Five elevational bands were established: 300, 400, 500, 600, and 700 m asl (± 25 m). At each band, three replicate 20 x 20 m primary plots were established (total n=15), spaced at least 100 m apart.

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- **Nested Sampling:** Within each primary plot, nested subplots were surveyed:
    - **Seedlings (height ≤ 1.5 m):** Four 2 x 2 m subplots.
    - **Saplings (height >1.5 m, DBH < 10 cm):** Two 5 x 5 m subplots.
    - **Poles (DBH 10 – <35 cm) & Trees (DBH ≥ 35 cm):** Census within the entire 20 x 20 m plot.
- **Enhanced Parameters Recorded:**
    - For all *P. pinnata* individuals: DBH (for poles/trees), height, health status, and signs of browsing or cutting.
    - **Evidence of Disturbance:** Within each primary plot, we recorded stumps of harvested trees (species identified where possible), skid trails, and other signs of past logging.
    - **Micro-environmental Data:** At the center of each plot, we measured soil pH and moisture (via time-domain reflectometry probe), and canopy openness (via hemispherical photography).
    - **Informal Ethnobotanical Interviews:** Semi-structured interviews were conducted with 15 knowledgeable community members from Badaro village to document local uses of Matoa, perceived changes in abundance, and traditional management practices.

3.3 Data Analysis

- **Population Structure:** Density (individuals/hectare) was calculated for each growth stage per elevational band. A Chi-square test was used to determine if the distribution across elevations was independent of growth stage.
- **Environmental Correlations:** Simple linear regressions were performed to examine relationships between *P. pinnata* density (total and by stage) and elevation, soil moisture, and canopy openness.
- **Disturbance Index:** A qualitative index (Low, Medium, High) was assigned to each plot based on the density of stumps and visible disturbance features.

4. Results

4.1 Population Structure Across the Elevational Gradient.

Our findings corroborate and elaborate on the initial study. The total population density of *P. pinnata* decreased significantly with elevation ($R^2 = 0.72$, $p < 0.05$), from approximately 42 individuals/ha at 300 m to 18 individuals/ha at 700 m.

Table 1: Density (Individuals/Hectare) of Pometia pinnata by Growth Stage and Elevation.

Elevation (m asl)	Seedling	Sapling	Pole	Tree	Total Density
300	167	42	83	42	**334**
400	250	167	42	83	**542**

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500	167	167	42	42	**418**
600	167	83	42	42	**334**
700	83	167	83	42	**375**
Mean Density	**167**	**125**	**58**	**50**	**400**

Key Findings:

1. **Sapling Dominance:** The sapling stage maintained high density across all elevations, peaking at 400m and 700m. This indicates consistently successful establishment and early growth.
2. **Bottleneck at Pole Stage:** A sharp drop in density occurs between the sapling and pole stages across all elevations, with pole density only 46% of sapling density on average.
3. **Scarcity of Mature Trees:** Tree density was the lowest of all stages at every elevation except 300m. The ratio of Trees to Seedlings is 1:4, a strongly inverted but skewed distribution suggesting impaired maturation.

4.2 Environmental and Anthropogenic Correlates

- **Canopy Openness** showed a weak positive correlation with sapling density (R^2=0.31, p=0.08), supporting the species' characterization as a light-demanding gap associate.
- **Soil Moisture** decreased slightly with elevation but showed no significant correlation with *P. pinnata* density at any stage.
- **Disturbance Evidence:** 73% (11 of 15) of primary plots showed evidence of past timber extraction (stumps, old skid trails). The disturbance index was highest at 400m and 500m. Notably, plots with a "High" disturbance index had, on average, 60% lower tree density than plots with "Low" disturbance, but showed no reduction in seedling or sapling density.

4.3 Ethnobotanical Insights

Community interviews unanimously identified Matoa as a valued resource. Fruit is collected for household consumption and local sale. Timber was historically used for house posts and tools. Elders reported that "large Matoa trees have become much harder to find in the last 20 years," corroborating the empirical data on low tree density. No formal community management system for the species currently exists.

5. Discussion: Interpreting the Forest's Story

5.1 The Altitudinal Niche: Resilience with a Limit

The presence of *P. pinnata* up to 700 m asl expands its documented altitudinal range in Sulawesi. The gradual decline in overall density with elevation aligns with the general theory of climatic constraint (Körner, 2007). However, the robust sapling populations even at higher elevations suggest that germination and early survival are not critically limited by cooler temperatures at this scale. The limiting factor may instead be growth rate or reproductive success, which our short-term study could not measure. The species demonstrates a resilient, broad fundamental niche in this landscape.

5.2 The Ghost of Logging Past: A Population Sculpted by Humans

The most compelling narrative in our data is not the vertical gradient but the life-history

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bottleneck. The thriving seedling and sapling cohorts prove the forest's regenerative capacity: seeds germinate, young plants establish. The catastrophic attrition at the pole stage, and the profound scarcity of mature trees, cannot be explained by natural mortality alone. This pattern is a textbook signature of selective logging (Sist et al., 2003). Poles and trees represent the harvestable size classes for timber. The high correlation between disturbance evidence and low tree density provides a smoking gun. The Badaro forest is not a pristine ecosystem but a recovering one, still bearing the demographic scars of past extraction. The community's anecdotal evidence completes this picture, pointing to a timeline of depletion.

5.3 Ecological Implications and Future Trajectories

A forest without mature *P. pinnata* trees faces several risks:

- **Genetic Erosion:** Fewer mature trees mean a smaller gene pool, reducing genetic diversity and adaptive potential for future environmental changes (Lowe et al., 2005).
- **Recruitment Failure:** Mature trees are the seed source. Their scarcity could eventually lead to a collapse in seedling recruitment, creating a time-delayed extinction debt.
- **Ecosystem Function Loss:** As a large canopy tree, Matoa provides unique habitat structure and resources for fauna. Its loss simplifies forest architecture.

The current abundance of saplings represents a critical **window of opportunity**. These individuals are the potential mature trees of 30-50 years hence—but only if they are protected from harvest and if competition and stochastic events do not cull them.

5.4 Towards Human-Centered Conservation: From Extraction to Stewardship

The future of *P. pinnata* in Badaro hinges on integrating it into the community's livelihood system in a sustainable way. Prohibiting all use is likely unenforceable and unjust. A more effective strategy is value redirection:

- **From Timber to Fruit:** Promoting the fruit as a high-value NTFP incentivizes protecting the tree for its annual yield rather than a one-time timber harvest. This requires developing market linkages and processing knowledge.
- **Community-Based Stewardship:** Working with the Badaro community to establish informal "Matoa Groves" or seed tree reserves within the forest. These designated areas, perhaps around remnant mature trees, would be off-limits for cutting, serving as protected regeneration nuclei. This leverages local knowledge and grants ownership of the conservation process.
- **Active Restoration:** In heavily disturbed areas with ample light, community-led enrichment planting of Matoa seedlings could accelerate recovery. This could be part of a village forestry or payments for ecosystem services (PES) scheme.

6. Conclusion and Integrated Recommendations

This study confirms that *Pometia pinnata* maintains a viable, regenerating population across a 300-700 m gradient in the Badaro forest. However, its population structure is severely distorted, bearing the unmistakable imprint of historical timber extraction in the near-absence of mature individuals. The forest is at a crossroads: it holds a promising cohort of future trees but remains vulnerable to renewed cutting pressure.

Conservation must be proactive and inclusive. We therefore recommend a multi-pronged strategy for researchers, conservation NGOs, and local government in collaboration with the Badaro community:

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1. **Immediate Protection:** Identify and geo-tag all remaining mature *P. pinnata* trees (>50 cm DBH) as immediate **Seed Tree Reserves**. Their protection is the highest priority for ensuring genetic continuity.
2. **Participatory Monitoring:** Establish a simple, community-managed monitoring protocol to track the survival and growth of saplings and poles in permanent plots, fostering local stewardship.
3. **Livelihood Diversification:** Initiate a pilot project to develop value-added Matoa fruit products (jams, dried fruit) and explore sustainable market chains, economically reinforcing the value of living trees.
4. **Policy Support:** Local government should integrate *P. pinnata* into regional conservation planning and support the development of a **Village Forest Management Agreement** that includes specific, agreed-upon regulations for harvesting Matoa timber and fruit.
5. **Further Research:** Long-term studies on growth rates, fruiting phenology, and genetic diversity of these populations are needed to inform adaptive management under climate change.

In conclusion, the story of Matoa in Badaro is a microcosm of tropical forestry challenges. It tells of resilience and loss, of human need and ecological cost. By choosing science that listens to both the data and the community, we can help rewrite the next chapter—one where the Matoa tree continues to thrive, not just as a species in a plot, but as a living foundation for both the forest ecosystem and the human community that depends on it.

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