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Carrying Capacity of Plantation Area as Habitat of Sumatran Elephant (*Elephas Maximus Sumatranus*) at Giam Siak Kecil Landscape, Riau

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ABSTRACT

The Sumatran elephant (*Elephas maximus sumatranus*) increasingly utilizes human-modified landscapes, including Industrial Tree Plantations (HTIs), as over 70% of its population now resides outside protected areas. However, the ecological capacity of HTIs to support viable elephant populations remains poorly quantified. This study assessed the habitat carrying capacity of HTI concessions in the Giam Siak Kecil landscape, Bengkalis Regency, Riau, Indonesia—a critical area adjacent to the Giam Siak Kecil Wildlife Reserve. Through field surveys across 51 plots in Eucalyptus pellita, Acacia crassicarpa, and Green Belt zones—stratified by age (0–4 years) and management intensity (managed vs. unmanaged)—we evaluated understory vegetation composition, biomass productivity, and elephant habitat use. A total of 82 plant species, many known elephant forage items, were recorded, with highest species richness in Eucalyptus stands and greatest diversity in Green Belts. Biomass productivity peaked in unmanaged 0-year Acacia stands (1,179.08 kg/ha/day), far exceeding that of older or managed stands. Carrying capacity estimates revealed that unmanaged, recently harvested Acacia plantations could support up to 202 elephants per 100 ha, whereas managed or mature Eucalyptus stands supported substantially fewer. Historical GPS collar data confirmed active use of these HTI areas by the Almira and Nae elephant groups, with movement corridors strongly aligned with riparian zones, Green Belts, and young regenerating stands. Our findings demonstrate that HTI ecological value for elephants is determined more by management practices and stand age than by land-cover type alone. We recommend integrating conservation-oriented silviculture—such as minimizing understory clearance, maintaining Green Belt connectivity, and aligning harvest cycles with elephant movement—into concession planning to enhance HTIs as functional components of a landscape-scale conservation strategy for the critically endangered Sumatran elephant.

1. INTRODUCTION

The Sumatran elephant (*Elephas maximus sumatranus*) is an iconic and endemic subspecies of Sumatra Island, critically dependent on the quality and availability of its natural habitat. This dependence stems from its ecological requirements for expansive ranging areas, diverse forest vegetation as food resources, and reliable access to water—all of which are adequately fulfilled only within intact natural habitats (Fernando *et al.*, 2020). Habitat loss and fragmentation resulting from land conversion for plantations, infrastructure, and human settlements have not only constricted elephant ranges but also intensified human–elephant conflict, posing a severe threat to the species' survival in the wild.

As the largest terrestrial mammal in Southeast Asia, the Sumatran elephant plays a vital ecological role as both a seed disperser and an ecosystem engineer, thereby influencing forest structure and composition. However, its continued existence is under serious threat due to habitat degradation and fragmentation—the foremost environmental challenges in Indonesia. The conversion of natural forests into Industrial Tree Plantations (HTI—Hutan Tanaman Industri) has significantly reduced elephant range areas and escalated human–elephant conflict. Population estimates indicate a dramatic decline of over 50% within just 33 years

(1984–2017), from 2,800–4,800 individuals to only 1,694–2,038 distributed across 36 population pockets in seven Sumatran provinces (Halawa *et al.*, 2024).

In Riau Province alone, the Sumatran elephant population is estimated to have plummeted by more than 85% over 34 years—from 1,067–1,617 individuals across 11 population pockets in 1984 to merely 148–176 individuals in seven pockets by 2018. This drastic reduction is primarily attributed to natural forest loss from land conversion and settlement expansion, which has fragmented the landscape and disrupted critical elephant migration corridors (Kuswanda *et al.*, 2022).

Although protected areas remain central to elephant conservation, recent studies reveal that over 70% of the Sumatran elephant population resides outside formal conservation zones—including within HTI concessions, plantations, and community lands. This underscores the emerging role of HTIs not merely as production landscapes but also as buffer habitats and potential ecological corridors for elephant persistence (Helida *et al.*, 2022). Unfortunately, the ecological functions of HTIs as wildlife habitats remain poorly integrated into concession management planning and are often overlooked.

Previous research has examined key ecological parameters such as vegetation cover, natural diet potential, spatial distribution, and minimum habitat area requirements necessary to support viable elephant populations (Fikri et al., 2023). Ecological modeling approaches have also been employed to predict habitat suitability and population dynamics under changing landscape conditions (Moßbrucker *et al.*, 2016; Wilson *et al.*, 2021; Imron *et al.*, 2023). However, these studies have largely focused on protected areas like national parks and nature reserves—zones already prioritized for high-level conservation. In contrast, assessments of elephant habitat carrying capacity within modified landscapes, particularly HTIs, remain scarce.

Yet, within the framework of landscape-based habitat management, HTIs hold strategic potential as components of a conservation matrix—especially if managed through ecosystem-based approaches and landscape ecology principles. The Giam Siak Kecil (GSK) landscape in Bengkalis Regency, Riau, represents one such critical area, where HTIs have become intensively utilized by Sumatran elephants, particularly in zones featuring young vegetation, shrublands, and natural or artificial water sources (Witanto, 2024). Despite this, challenges persist due to conflicting interests between industrial production and conservation, lack of ecological data, and limited corporate engagement in wildlife conservation initiatives (Ikhsan, 2021).

Given the urgent need for science-based, sustainable habitat management that balances industrial land use with biodiversity conservation, there is a critical knowledge gap regarding the quantitative carrying capacity of modified HTI landscapes to support viable Sumatran elephant populations. This study therefore aims to analyze the carrying capacity of HTI areas in Bengkalis Regency to inform evidence-based strategies for habitat management, human–elephant conflict mitigation, and policy development that integrates conservation into modified landscapes.

2. LITERATURE REVIEW

Carrying capacity of elephant habitat refers to the ecological ability of a given landscape to sustainably provide essential resources—primarily food and water—required to support a viable elephant population over the long term. This metric is typically calculated based on daily forage productivity, the area covered by edible vegetation, the proper use factor (PUF), and the daily dietary requirements per individual elephant (Garsetiasih et al., 2018; Susetyo, 1980). In conservation biology, carrying capacity is not merely a static measure of biomass but a dynamic indicator that reflects the interplay between ecological productivity, spatial configuration, and species-specific behavioral adaptations.

Industrial Tree Plantations (HTIs) are intensively managed forest areas dominated by fast-growing monocultures—primarily Acacia crassicarpa or Eucalyptus pellita—established for wood-based industrial production (Ministerial Regulation of Environment and Forestry No. P.11/MENLHK/SETJEN/PLB.3/2018). Although HTIs are not natural habitats, they may function as partial substitutes or ecological buffers if managed with conservation principles in mind. Given that Sumatran elephants require expansive home ranges (typically 50–300 km² per group; Fernando *et al.*, 2008; Williams *et al.*, 2020), the spatial quality and connectivity of HTIs can significantly influence their movement patterns and long-term persistence.

The Sumatran elephant, a subspecies endemic to Sumatra, exhibits complex ecological needs shaped by its role as both a seed disperser and an ecosystem engineer (Fernando *et al.*, 2020). Daily dietary intake ranges from 150 to 200 kg of vegetative biomass, primarily drawn from families such as Poaceae, Rubiaceae, Cyperaceae,

and Zingiberaceae (Fernando *et al.*, 2021; Wibowo *et al.*, 2022). Consequently, habitats that sustain heterogeneous understory vegetation—including grasslands, shrublands, secondary forests, and reliable water sources—are critical for long-term viability.

Landscape ecology theory further posits that the spatial arrangement of habitat patches—particularly their size, shape, and connectivity—profoundly affects population dynamics of large, mobile species (Fahmy et al., 2015). In the fragmented landscapes of Riau Province, HTIs often form part of a multifunctional landscape matrix that bridges protected areas like the Giam Siak Kecil Wildlife Reserve (GSK). When managed appropriately, such matrices can facilitate elephant movement and mitigate isolation, thereby reducing the risk of local extinctions (Winarno & Harianto, 2018).

However, the conservation value of HTIs is highly dependent on management practices. Intensive silvicultural interventions—such as weeding, herbicide application, and understory clearance—can drastically reduce plant diversity and forage availability, diminishing their suitability for elephants (Pratiwi *et al.*, 2023; Wijaya et al., 2022). Conversely, less intensive or selectively managed HTI blocks, particularly those incorporating green belts or riparian buffers, can enhance habitat connectivity and provide critical seasonal forage, especially during dry periods when primary forests offer limited resources (Rahman *et al.*, 2020; Nofiandi *et al.*, 2023).

Previous studies on elephant carrying capacity have largely focused on natural ecosystems. For instance, Mahanani (2012) evaluated forage availability and vegetation structure in Way Kambas National Park, correlating these with elephant density in protected lowland forests. Similarly, Moßbrucker *et al.* (2016) and Imron *et al.* (2023) employed ecological niche modeling (MaxEnt) and spatial resource models, respectively, to predict suitable elephant habitats in southern and central Sumatra—but exclusively within natural forest contexts.

These studies provide robust baselines but overlook the growing reality that over 70% of Sumatran elephants now inhabit non-protected, human-dominated landscapes, including HTIs, oil palm plantations, and community lands (Helida *et al.*, 2022). This demographic shift underscores an urgent need to evaluate the ecological capacity of production landscapes to support viable elephant populations—a gap this study directly addresses.

By integrating field-based vegetation analysis, dietary preference data, and spatial movement patterns (via GPS collar records), this research tests the hypothesis that HTIs—despite their engineered nature—can function as functional components of a landscape-scale conservation strategy if managed with multifunctional principles. This aligns with contemporary conservation paradigms emphasizing coexistence, matrix permeability, and the integration of biodiversity goals into working landscapes (Daily *et al.*, 2009; Fischer *et al.*, 2017).

3. METHOD

Study Area and Period

This study was conducted in the concession areas of industrial forest plantation (HTI—Hutan Tanaman Industri) companies located in Bengkalis Regency, Riau Province, Indonesia, as well as within the adjacent Giam Siak Kecil Wildlife Reserve (Suaka Margasatwa Giam Siak Kecil, or GSK). Field data collection spanned four consecutive monthly phases from September to December 2024. The study landscape comprises heterogeneous land-cover types, including *Eucalyptus pellita* and *Acacia crassicarpa* plantations of varying ages (0–4 years), secondary shrubland, and natural forest fragments, all of which serve as potential elephant foraging or movement zones.

Study Subjects and Focal Elephant Groups

The focal species was the Sumatran elephant (*Elephas maximus sumatranus*), specifically two known wild groups regularly utilizing the study landscape: (1) Almira group (~18 individuals; formerly tracked via a GPS collar deployed on an individual named Seruni); (2) Nae group (~25 individuals; formerly tracked via a GPS collar on an individual named Rara)

These groups have been consistently monitored by the Riau Natural Resources Conservation Agency (BKSDA Riau) and conservation partners. Although collar transmissions ceased approximately one year prior to this study due to satellite subscription expiration, historical GPS data and recent field sign (dung, tracks, wallows) confirmed ongoing use of the HTI concession as part of their home ranges.

Data Collection

Vegetation and Elephant Habitat Assessment

A combined transect–quadrat sampling design was employed. Sampling plots were positioned using purposive sampling, guided by: (a) recent elephant signs (dung, tracks, bark stripping, wallows), (b) land-cover

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map interpretation, and (c) historical GPS collar trajectories. Each sampling unit comprised a main transect (1,000 m long × 20 m wide) with systematically placed subplots (Figure 3 in original thesis).

Herbaceous Vegetation and Diet Inventory

Within each land-cover type, herb-layer vegetation potentially consumed by elephants was inventoried using nested sampling:

- Plot layout: For herbaceous vegetation and seedlings, twelve 1 m × 1 m quadrats were established along each transect at 50 m intervals.
- Biomass measurement: Aboveground green biomass was harvested via hand clipping at 5 cm above ground level. Sampling was repeated twice per plot at a 20-day interval to estimate regrowth and daily productivity (adapted from Mahanani, 2012).
- Sample processing: Fresh (wet) biomass was weighed in the field; a subsample was oven-dried to constant weight to determine dry matter content and calculate dry biomass per hectare.

Land-Use and Management Stratification

A total of 51 sampling plots were established across three dominant vegetation types in the HTI concession: (1) *Eucalyptus pellita* (41 plots across age classes 0–4 years and management treatments); (2) *Acacia crassicarpa* (6 plots across age classes 0–3 years); (3) Green belt (3 plots; semi-natural riparian or buffer zones). Plots were further stratified by management treatment: (1) Managed: plots subjected to standard silvicultural practices, including mechanical/manual weeding, periodic fertilization, and understory clearance to reduce competition with canopy trees; (2) Unmanaged: plots left without human intervention, allowing natural vegetation succession.

Elephant Habitat Use Indicators

Habitat utilization by elephants was confirmed through field signs, including: fresh dung and tracks; wallows and mineral lick sites; bark stripping, broken branches, and feeding remains; corroborating interviews with HTI field staff and conservation rangers. Recorded environmental variables included: (a) natural diet species composition, (b) air temperature and relative humidity, (c) canopy cover (estimated visually), (d) water and mineral availability, and (e) presence/condition of wallows.

Data Analysis

Vegetation Structure and Composition

Vegetation data were analyzed using the Important Value Index (INP) using these formula:

Density	$\frac{Number\ of\ Individuals\ of\ a\ Species\ in\ a\ Sample\ Unit}{Total\ Area\ of\ Sample\ Unit} x\ 100$
Relative Density	$\frac{Density\ of\ A\ Species}{Density\ of\ Total\ Species}\ x\ 100\%$
Frequency	$\frac{Number\ of\ Individuals\ of\ a\ Species\ in\ a\ Sample\ Unit}{Total\ Plots} x\ 100$
Relative Frequency	$\frac{Frequency\ of\ A\ Species}{Frequency\ of\ Total\ Species} x\ 100$
Dominancy	$\frac{Number\ of\ Area\ Size\ of\ a\ Species\ in\ a\ Sample\ Unit}{Total\ Area\ Size\ of\ Sample\ Unit} x\ 100$
Relative Dominancy	$\frac{Dominancy\ of\ A\ Species}{Dominancy\ of\ Total\ Species}\ x\ 100\%$
Important Value Index	IVI = KR + FR

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Biomass and Productivity Estimation

Dry biomass (BK, Berat Kering) was derived from wet weight (BB, Berat Basah) using a standard conversion factor. Biomass per hectare was calculated as:

$$\text{Total BK} = \frac{BK\ sub\ contoh\ (gr)}{BB\ sub\ contoh\ (gr)} \text{ x Total BB (gr)}$$

$$\text{Biomassa BK / ha} = \frac{BK\ sub\ contoh\ (gr)}{BB\ sub\ contoh\ (gr)} \text{ x } 10.000$$

Species Diversity Index

To determine the diversity of understory plant species as a food source for Sumatran elephants at the study site, the Shannon-Wienner diversity index (*H'*) was used, namely:

$$H' = -\sum (Pi)\ (InPi)$$

Explanation:
H' = diversity index
Pi = ni/N, the ratio between the number of individuals of species 1 and the total number of individuals
Ni = number of individuals of species i
N = total number of individuals

The criteria for the Shannon-Wiener diversity index are as follows:
H'<1 = Low diversity
1<H'<3 = Moderate diversity
H'>3 = High diversity

Margalef Species Richness Index (D)

$$D = \frac{S - 1}{\text{In N}}$$

Explanation:

D = Margalef index of species richness
S = Number of species (species richness)
N = Total number of individuals of all species
ln N = Natural logarithm of N

Pielou's Evenness Index (E)

The evenness of individual distribution is calculated using the Evenness Index with the formula:

$$E = H'/(\ln S)$$

Explanation:
E = Evenness Index
H' = Shannon-Wienner Individual Diversity Index
S = Number of species found

The E value ranges from 0-1. A value close to 0 indicates a dominant species in the community. A value close to 1 indicates that all species have almost the same level of evenness.

Elephant Habitat Carrying Capacity

Carrying capacity (in elephants per hectare) was calculated using the standard formula (Susetyo, 1980; Garsetiasih *et al.*, 2018):

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$$\text{Carrying capacity} = \frac{P \text{ x } pu \text{ x A}}{\text{C}} \text{ (ha/individual)}$$

where:
P = daily forage production (kg/ha/day)
pu = proper use factor (set at 60% based on flat topography, 0–5° slope)
A = area covered by forage vegetation (ha)
C = daily dietary requirement per elephant (350 kg/day, based on literature)

Elephant Movement and Space Use

Historical GPS locations from collared individuals (Seruni, Rara, Almira, Nae) were analyzed using Kernel Density Estimation (KDE) in ArcGIS Pro 3.0 to delineate home ranges:

- Cell size: 50 m × 50 m
- Bandwidth selection: Least Squares Cross Validation (LSCV)
- Home range contours: 50% isopleth (core area), 95% isopleth (total home range)
- This spatial analysis allowed quantification of elephant density and overlap with HTI land-cover types. (partners).

4. RESULT AND DISCUSSION

Study Area and Observed Elephant Activity

The research was conducted in industrial tree plantation (HTI) concessions managed by PT. Arara Abadi and PT. Riau Abadi Lestari in Bengkalis Regency, Riau Province, adjacent to the Giam Siak Kecil Wildlife Reserve (GSK). This landscape is recognized as one of seven priority elephant conservation areas in Indonesia and supports an estimated 100–150 individuals of *Elephas maximus sumatranus*. Field observations and historical GPS collar data confirmed active use of HTI areas by at least two elephant groups: Almira (~18 individuals) and Nae (~25 individuals). Elephant presence was consistently evidenced by dung, tracks, wallows, bark stripping, and feeding remains across multiple vegetation types, confirming HTIs as non-protected but functionally significant habitats in the GSK elephant landscape.

Vegetation Composition and Species Richness

A total of 82 plant species from 54 families were identified across the three main HTI vegetation types: *Eucalyptus pellita* (64 species), *Acacia crassicarpa* (23 species), and *Green Belt* (38 species) (Table 1). Dominant families included Poaceae, Rubiaceae, Cyperaceae, Zingiberaceae, and Pteridaceae, reflecting the herbaceous and shrub-layer composition typical of disturbed tropical lowland ecosystems. Notably, species richness was highest in Eucalyptus pellita stands, despite their monocultural management, suggesting that canopy age and microclimatic conditions foster greater understory diversity than in Acacia plantations.

This pattern aligns with ecological succession theory: younger stands (0–2 years) hosted pioneer species such as Ageratum conyzoides, Ehrharta erecta, and Clidemia hirta, whereas older stands (3–4 years) showed increased representation of shade-tolerant ferns (e.g., Stenochlaena palustris, Nephrolepis biserrata) and woody climbers (e.g., Cayratia japonica). The persistence of diverse understory vegetation—even in intensively managed HTI—highlights the potential of these landscapes to support dietary resources for megaherbivores.

Table 1. List of understory plant species in the Eucalyptus, Acacia, and Greenbelt plantation areas in the HTI-GSK region

Species			
No.	**Species Name**	**Vern. Name**	**Family**
1	*Axonopus compressus*	Rumput paitan, Gajah mini	Poaceae
2	*Cyrtococcum patens*	Rumput telor ikan, Kasup	Poaceae
3	*Digitaria sp.*	Rumput jari	Poaceae
4	*Ehrharta erecta*	Rumput teteles, Rumput Panik	Poaceae
5	*Eleusine indica*	Rumput belulang, Jampang	Poaceae
6	*Imperata cylindrica*	Alang alang, Ilalang	Poaceae

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Species

No.	Species Name	Vern. Name	Family
7	*Lophaterum gracile*	Rumput bambu, Tangkur gunung	Poaceae
8	*Ottochloa nodosa*	Rumput sarang buaya, Kawat	Poaceae
9	*Paspalum conjagatum*	Rumput Pahit, Rumput kerbau	Poaceae
10	*Tripsacum dactyloides*	Rumput Gamma Timur	Poaceae
11	*Flagellaria indica*	Bambu rambat, Rotan palsu	Flagellariaceae
12	*Cyperus esculentus*	Teki Kuning	Cyperaceae
13	*Cyperus rotundus*	Rumput Teki atau Teki ladang	Cyperaceae
14	*Isolepis cernua*	Rumput fiberoptik, rumbai	Cyperaceae
15	*Stenochlaena palustris*	Pakis udang, Kresek, Kalakai	Blacnaceae
16	*Cystopteris fragilis*	Pakis Rapuh, pakis kandung	Cystopteridaceae
17	*Dipcranopteris linearis*	Paku resam atau paku andam	Glecneiceae
18	*Lygodium microphyllum*	Akar kawek dan pakis panjat	Lygodiceae
19	*Palhinhaea cenua*	Paku kawat	Nephrolepidaceae
20	*Nephrolepis biserrata*	Paku pedang dan paku uban	Nephrolepidaceae
21	*Pityrogramma calomelanos*	Paku Perak	Pteridaceae
22	*Taenitis blachnoides*	Paku Ringin	Pteridaceae
23	*Crinum asiaticum*	Bakung putih, Bunga Patil lele	Amaryllidaceae
24	*Calamus ciliaris (sp.)*	Rotan cacing, Palem paris	Arecaceae
25	*Dianella ensifolia*	Rumput Siak Siak, Dewangga	Asphodelaceae
26	*Curculigo orchioides*	Congkok, Sambiroto	Hypoxidaceae
27	*Etlingera coccinera*	Tepusan, Kecalak, Bowooi	Zingiberaceae
28	*Asystasia gangetica*	Arasungsang	Achantaceae
29	*Asystasia sp*	Ara sunsang	Achantaceae
30	*Ageratum conyzoides*	Babandotan, Siangit, Wedusan	Asteraceae
31	*Crassocephalum crepidioides*	Sintrong dan Jambrong	Asteraceae
32	*Chromolaena odorata*	Minjangan, Kirinyuh	Asteraceae
33	*Mikania micranta*	Sembung rambat	Asteraceae
34	*Croton glandolosus*	Puring daun gigi, Puring tropis	Eurphorbiaceae
35	*Aeschynanthus pulcher*	Jarong atau Sangko hidung	Gesneriaceae
36	*Pericampylus glaucus*	Akar telur, akar gamat	Menispermaceae
37	*Passiflora foetida*	Kaceprek & Markisa mini	Passifloraceae
38	Passiflora suberosa	Konyal atau Akar kekunyit	Passifloraceae
39	*Hedyotis sp.*	Rumput siku-siku, lidah ular	Rubiaceae
40	*Spermacoce alata*	Rumput setawar & Goletrak	Rubiaceae
41	*Spermacoce remota*	Rumput kancing palsu hutan	Rubiaceae
42	*Smilax anceps*	Pokok Banar	Smilaceae
43	*Smilax bracteata*	Pokok Banar, Tongkung	Smilaceae
44	*Cayratia japonica*	Anggur hutan, Ketirem	Vitaceae
45	*Cissus verticillata*	Anggur putri, Tanaman tirai	Vitaceae
46	*Tabernaemontana divaricata*	Mondokaki, Kembang mentega	Apocynaceae
47	*Sieruela rutidosperma*	Maman Lanang, Maman ungu	Cleomaceae
48	*Clidemia hirta*	Senduduk Bulu, daun sabun	Melastomaceae

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Species			
No.	**Species Name**	**Vern. Name**	**Family**
49	*Melastoma malabathricum*	Harendong dan Senduduk	Melastomaceae
50	*Solanum mauritianum*	Tembakau Liar, Cepokak Hutan	Solanaceae
51	*Pottsia laxiflora*	Pottsia	Apocynaceae
52	Tetracera indica	Akar mempelas, Kasapan	Dilleniaceae
53	*Spatholobus sp*	Kesarek, Aka Kalesi	Fabaceae
54	*Bauhinia semibifida*	Kupu rambat, Kangkang katup	Fabaceae
55	*Callerya sp.*	Callerya	Fabaceae
56	*Annona sp.*	Anona	Annonaceae
57	*Cerbera manghas*	Bintaro, Mangga laut	Apocynaceae
58	*Canarium sp*	Kenari	Burseraceae
59	*Trema orientalis*	Anggrung, mengkirai	Canabaceae
60	*Dillenia sp*	Simpur, Apel gajah	Dilleniaceae
61	*Shorea sp*	Meranti, Seraya	Dipterocarpaceae
62	*Shorea uliginosa*	Meranti batu	Dipterocapaceae
63	*Macaranga sp.*	Kayu Mahang, Maang	Eurphorbiaceae
64	*Mollatus paniculatus*	Tutup Putih, Balik Angin	Euphorbiaceae
65	*Mollatus sp*	Balik Angin, Balek Angin	Euphorbiaceae
66	*Acacia mangium*	Akasia, Tongke hutan	Fabaceae
67	*Adenanthera pavonina*	Saga, Segawe sabrang	Fabaceae
68	*Archidendron bubalinum*	Kabau, jering utan	Fabaceae
69	*Litsea sp*	Kayu Modang	Lauraceae
70	*Leea indica*	Kayu Tuwa, Girang, Sangeh	Leeaceae
71	*Adansonia digitate*	Adansonia	Malfaceae
72	*Ficus ampelas*	Pohon Hampelas atau Amplas	Moraceae
73	*Artocarpus champeden*	Cempedak hutan, Nongko cino	Moraceae
74	*Eucalyptus pellita*	Ekaliptus	Myrtaceae
75	*Maesa sp.*	Daun entok	Primulaceae
76	*Maesa perlarius*	Kayu Nasi	Primulaceae
77	*Prunus laurocerasus*	Cherry laurel	Rocaceae
78	*Mycetia sinensis*	Pohon kopi-kopian	Rubiaceae
79	*Nauclea officinalis*	Bengkal bengkal	Rubiaceae
80	*Psychotria sp.*	Kopi hutan	Rubiaceae
81	*Melicope ptelefolia*	Tenggek burung, Cabang tiga	Rutaceae
82	*Casearia membranasia*	Casearia	Salicaceae

Vegetation Dynamics and Recovery Post-Harvest

Eucalyptus pellita, cover declined from 32.0% to 15.1% one month post-harvest but recovered to 47.2% by the third month in 4-year-old stands. Similarly, *Acacia crassicarpa* stands showed initial decline (from 35.5% to 5.0%) but slower recovery, indicating lower resilience. In contrast, Green Belt zones maintained stable cover (~5%) throughout the study period, underscoring their role as ecologically buffered transition zones. Vegetation recovery capacity is influenced by both stand age and species identity: older Eucalyptus stands supported faster and more complete regeneration, likely due to accumulated organic litter, canopy closure, and soil moisture retention. This supports the view that HTI management cycles—particularly rotation length and post-harvest

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retention—can be optimized to maintain forage continuity for elephants.

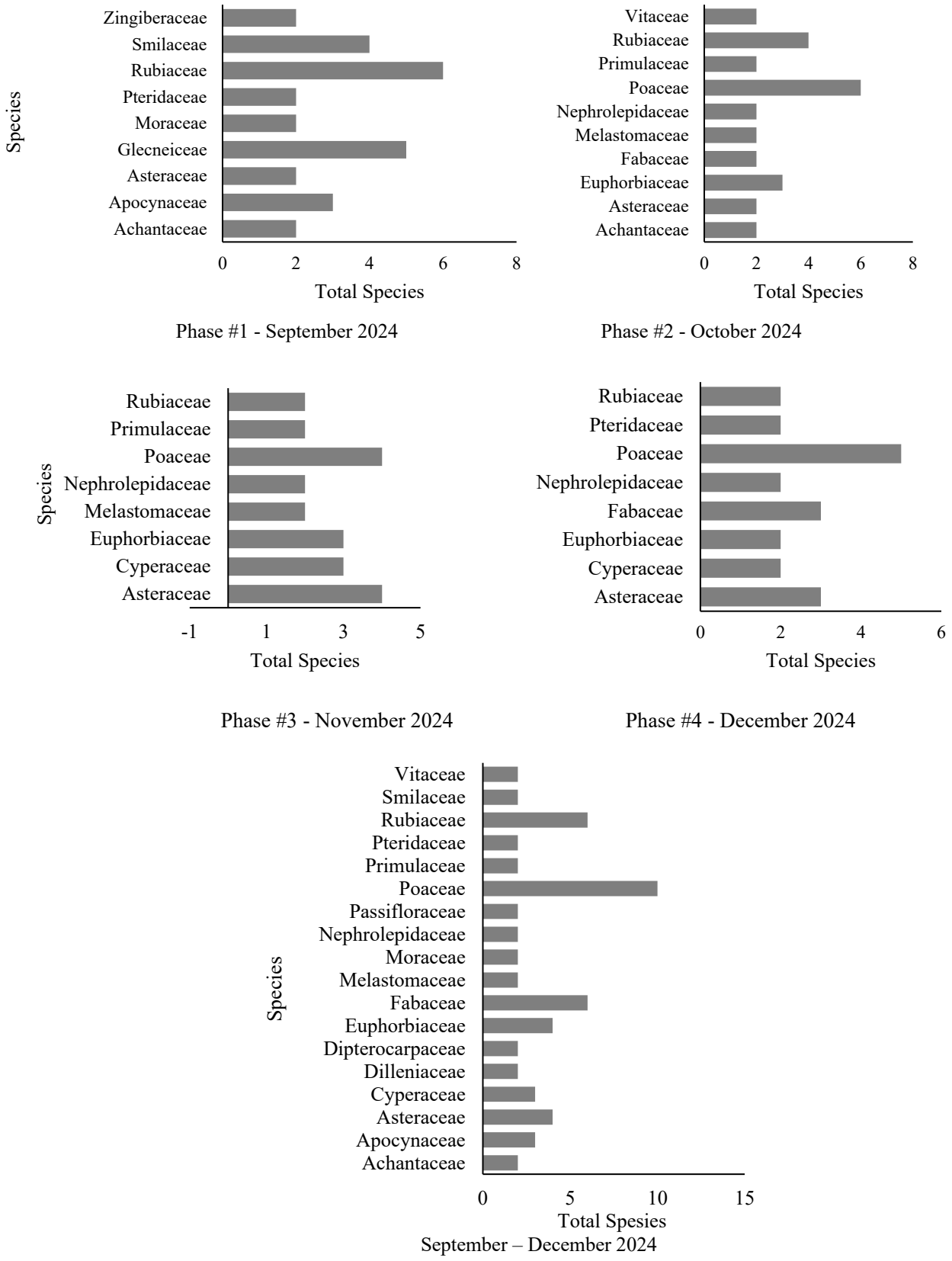


Figure 1. Composition of dominant families in Sumatran elephant habitat vegetation plots in the Giam Siak Kecil (GSK) industrial timber concession area.

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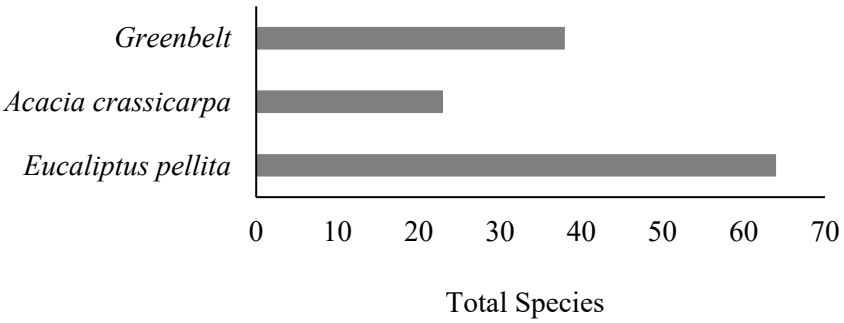


Figure 2. Number of Understory Plant Species in the Giam Siak Kecil (GSK) Industrial Timber Plantation Concession in Areas Planted with Eucalyptus pellita, Acacia crassicarpa, and Green Belt

Biodiversity and Community Structure

Biodiversity indices revealed significant variation across management treatments and vegetation types. The Green Belt exhibited the highest Shannon–Wiener diversity (H′ = 3.14), species richness (D = 7.14), and evenness (E = 0.86), confirming its ecological superiority as a habitat matrix. Among plantation types, Eucalyptus pellita stands (especially at 3–4 years) showed moderate diversity (H′ = 2.65–2.72), while Acacia crassicarpa consistently recorded lower values (H′ = 1.31–2.16).

Crucially, unmanaged plots generally outperformed managed ones in all diversity metrics, indicating that silvicultural interventions—such as weeding and herbicide application—reduce floristic heterogeneity. This corroborates findings by Pratiwi et al. (2023) and Wijaya et al. (2022), who reported up to 40–60% reductions in understory diversity due to intensive HTI management. The dominance of disturbance-tolerant species like Clidemia hirta (INP = 53.47%) and Ottochloa nodosa (INP = 30.75%) in unmanaged plots further suggests that minimal intervention promotes early-successional communities that are highly palatable to elephants.

Biomass Productivity and Forage Availability

The highest productivity was recorded in unmanaged 0-year Acacia crassicarpa (1,179.08 kg/ha/day), followed by unmanaged Acacia at 1 and 2 years (945.87 and 860.02 kg/ha/day, respectively). In contrast, Eucalyptus pellita showed lower productivity (122.88–190.51 kg/ha/day), with a sharp decline in 3-year managed stands (89.40 kg/ha/day). The Green Belt produced 226.03 kg/ha/day—moderate but ecologically stable.

High-productivity Acacia plots, particularly in early successional stages, offer abundant, rapidly regenerating herbaceous biomass—key for sustaining elephant dietary demands (150–200 kg/day per individual). The low productivity of older Eucalyptus stands, however, may limit their value as long-term foraging habitats unless managed to encourage understory retention.

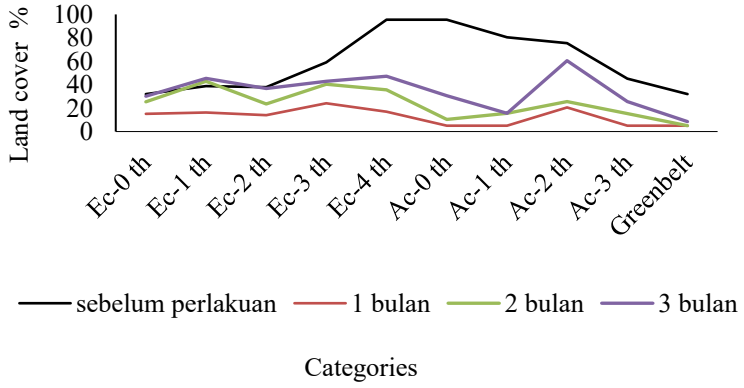


Figure 2. Percentage (%) of understory cover before and after harvesting treatment in areas of Eucalyptus pellita, Acacia crassicarpa, and Greenbelt.

DOI: https://doi.org/10.32663/.....

Habitat Use and Dietary Preferences

Of the 82 recorded species, 34 (41.46%) were classified as frequently consumed by elephants. Preference intensity varied by vegetation type: 52.17% of species in Acacia stands were preferred, compared to 45.31% in Eucalyptus and 36.84% in Green Belt. Highly consumed species included *Axonopus compressus, Ottochloa nodosa, Melastoma malabathricum, Clidemia hirta, and Etlingera coccinera*—all soft-leaved, fast-growing, and nutrient-rich.

This selective foraging behavior aligns with optimal foraging theory: elephants prioritize species with high digestibility and rapid regeneration. The lower preference for Green Belt species may reflect structural complexity and reduced accessibility rather than nutritional inadequacy. Notably, 14 species occurred across all three vegetation types, and 7 (50%) of these were preferred, suggesting that widespread, adaptable species are key dietary components.

Carrying Capacity Estimates

- Unmanaged 0-year Acacia: 202 elephants
- Managed 0-year Acacia: 114 elephants
- Unmanaged 4-year Eucalyptus: 21 elephants
- Green Belt: 39 elephants

The landscape-wide average was 76 elephants per 100 ha, indicating that HTI can support substantial elephant numbers—but only under specific conditions: young stands, minimal intervention, and high understory retention. These findings challenge the assumption that HTIs are inherently unsuitable for wildlife; instead, they reveal that management practices, not land-use designation alone, determine ecological value.

Elephant Movement Patterns and Spatial Use

Kernel Density Estimation (KDE) of historical GPS collar data revealed distinct movement patterns:

- Seruni: 37,000 ha total range; 5,466 ha core (high-intensity) zone
- Rara: 21,842 ha; 885 ha core
- Almira: 9,420 ha; 468 ha core
- Nae: 15,059 ha; 401 ha core

Elephant activity was spatially concentrated in southeastern concession areas near Duri II Melibur, with high overlap between Almira and Nae groups. Critically, movement corridors consistently aligned with riparian zones, Green Belts, and young Eucalyptus stands—confirming that structural connectivity and forage quality jointly shape elephant spatial ecology in modified landscapes.

Human activity (e.g., logging, road networks) was densest in operational cores (5,817 ha “very dense” zone), while peripheral and protected areas (e.g., SM Balai Raja) remained relatively undisturbed. This spatial segregation suggests that strategic zoning—reserving high-quality forage patches as no-go areas—could mitigate human–elephant conflict.

Synthesis: HTI as a Functional Component of Elephant Conservation

This study demonstrates that HTIs in the GSK landscape are not merely production zones but active components of the elephant habitat matrix. Three key insights emerge:

1. Management intensity matters more than land cover: Unmanaged or lightly managed HTI blocks support higher biodiversity, greater forage productivity, and stronger elephant use than intensively weeded stands.
2. Temporal dynamics are critical: Young stands (0–2 years) offer peak forage value, suggesting that rotational harvesting—if synchronized with elephant movement—can maintain landscape-scale forage continuity.
3. Green Belts are necessary but insufficient: While Green Belts enhance connectivity and stability, their forage quality is lower than that of regenerating plantation stands.

These findings support a multifunctional landscape approach (Fischer & Lindenmayer, 2007; Daily et al., 2009), wherein HTI concessions are managed not just for timber but as stepping stones in a regional conservation network. Integrating ecological data into concession-level planning—such as designating high-carbon, high-biodiversity blocks as elephant corridors—can align industrial forestry with national biodiversity goals.

5. CONCLUSIONS

This study offers both theoretical and practical contributions within the framework of landscape-based conservation and ecological carrying capacity theory by examining the potential of Industrial Tree Plantations (HTIs) as functional components of Sumatran elephant (*Elephas maximus sumatranus*) habitat in the Giam Siak Kecil Landscape. Although HTIs were not originally designed for conservation purposes, they exhibit a notably heterogeneous understory vegetation structure, hosting 82 plant species—an assemblage that substantially enhances the availability of potential forage for elephants.

Among the surveyed plots, recently harvested (0-year-old) Acacia crassicarpa stands that received no post-harvest management demonstrated the highest carrying capacity—equivalent to supporting approximately 200 elephants. This underscores the critical need to incorporate forest management practices into carrying capacity models, rather than relying solely on natural ecological variables. Nevertheless, current HTI conditions in Bengkalis Regency remain inadequate for fully meeting the optimal requirements of Sumatran elephants, particularly regarding forage quality, year-round resource stability, and ecological connectivity between HTI areas and adjacent natural forests in the Giam Siak Kecil (GSK) landscape. To enhance the supportive role of HTIs as supplementary habitats, specific recommendations include maintaining Green Belt corridors, minimizing the frequency of understory vegetation clearing, and aligning harvesting cycles with elephant movement patterns.

Furthermore, movement analysis based on historical GPS collar data revealed distinct behavioral differences among elephant groups: the Seruni group exhibited extensive spatial influence and significant impact on land-cover dynamics across the concession, whereas the Nae group displayed more localized movement patterns. These findings highlight how elephant space-use strategies are shaped by— and responsive to— the structure of human-modified landscapes.

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