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Evaluating browsing damage to selected taxa in a trial plantation within the Lungmanis Forest Reserve, Sabah, Malaysia

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Abstract. *Majapun RJ, Paul V, Suis MAF, Khoo E, Guanih VS, Kelvin PKN, En CT, Ajik M. 2024. Evaluating browsing damage to selected taxa in a trial plantation within the Lungmanis Forest Reserve, Sabah, Malaysia. Biodiversitas 25: 3540-3553.* The study assessed the impact of wildlife pests on seven tree taxa, including *Acacia crassicarpa, Eucalyptus pellita, Falcataria moluccana, Khaya ivorensis, Neolamarckia cadamba, Terminalia copelandii*, and *Swietenia macrophylla*, in trial plantations within Sabah's Lungmanis Forest Reserve, Sabah, Malaysia. Browsing damage was measured for all taxa at two time points (t1 and t2) using three indices (H-Index, S-Index, and PS-Index). The study revealed that *E. pellita, A. crassicarpa,* and *K. ivorensis* resisted browsing damage. At the same time, other species, such as *N. cadamba* and *F. moluccana*, suffered significant damage, with tree height losses between 50% and 70% due to wildlife pest activity. The study recorded high damage intensity for the PS-Index in the "Shooting" category. It also showed that subplot configurations with open (D) and fenced (A) plots exhibited similar levels of "Shooting," uncovering that some wildlife pests, like Sambar deer (*Rusa unicolor* (Kerr, 1792)) and pig-tailed macaques (*Macaca nemestrina* (Linnaeus, 1766)), were not entirely deterred by fencing and repeatedly browsed their preferred taxa. Additionally, *N. cadamba* was more susceptible to pest defoliators following the browsing damage than other taxa. The research highlights the limitations of fencing as a mitigation measure for wildlife-induced tree damage and underscores the need for a comprehensive wildlife management approach in forest plantations. This includes understanding wildlife behavior and human impact factors beyond population density and emphasizes the importance of species selection and plot configuration in managing wildlife-induced damage.

Keywords: Browsing damage, post survival, taxa trial, tree plantation, wildlife pest

Abbreviations: Acra: *Acacia crassicarpa*; Epel: *Eucalyptus pellita*; Falc: *Falcataria moluccana*; FRC: Forest Research Centre; FR: Forest Reserve; H-Index: Health; Khay: *Khaya ivorensis*; Neom: *Neolamarckia cadamba*; PS-Index: Post Survival; Term: *Terminalia copelandii*; Smac: *Swietenia macrophylla*; S-Index: Severity

INTRODUCTION

Present-day Sabah (Malaysia) faces the depletion of timber resources from its natural forests, prompting the adoption of commercial forest plantations as a viable solution. In 1974, Sabah Softwoods Sdn. Bhd. was established as a joint venture between Yayasan Sabah and North Borneo Timber, becoming the pioneering private venture in the commercial plantation industry. The company initiated the planting of approximately 60,000 hectares of exotic pine trees (*Pinus caribaea* Morelet and *P. oocarpa* Schiede ex Schltdl.). Over time, the industry gained momentum and now encompasses more than 300,000 hectares of forest plantation area, which includes research sites for experimental plantations (Sabah Forestry Department 2019). The Sabah Forestry Department has set up research plots in Forest Reserve (FR) stations like Sibuga, Gum-Gum, Kolapis, Segaliud Lokan, Telupid, Sosopodon, and Sook to improve plantation methods and combat pest and disease issues (Kamziah et al. 2011). However, the persistent risk of premature planting failure due to browsing mammals and pathogen attacks is a significant challenge that needs to be addressed to ensure productivity and investment security for private companies and smallholders involved in tree plantations (Moe et al. 2016; Lee 2018).

Mammal herbivory in forest plantation sites exemplifies human-wildlife conflict in Borneo. Studies on wildlife herbivory in forest plantations are scarce, resulting in limited knowledge about its impact, particularly from a financial perspective and integrated pest management strategies. In contrast, wildlife pests in oil palm plantations have been extensively studied (Santosa and Rejeki 2018; Amit and Tuen 2019). Selective browsing by wildlife has caused significant damage to monoculture tree plantations, posing an economic risk (Mikich and Liebschh 2014; Latham et al. 2019; Champagne et al. 2021; Suzuki et al. 2021) that often correlates with the population density of mammals within the forest network. For example, plantations near forest reserves may experience more damage due to higher deer densities (Abe et al. 2022; Otani et al. 2022). Additionally, competition for food resources increases browsing, particularly when plant availability is low due to deforestation and habitat fragmentation (Gaudry et al. 2022). The removal of understorey vegetation disrupts wildlife food sources, affecting forest regeneration and tree recruitment, which are vital for ungulates (Camargo-Sanabria et al. 2015; Pablo-Rodríguez et al. 2023).

In Sabah, Malaysia, the conversion of forests into monoculture plantations has altered the behavior of species like the bearded pig (*Sus barbatus* Müller, 1838)) and sambar deer (*Rusa unicolor* Kerr, 1792), pushing them into plantation areas and roads in search of food (Laneng et al. 2021; Nakabayashi et al. 2024). While population density plays a vital role, vegetation availability and landscape features also significantly impact browsing damage in tropical forests. Various damage control measures, such as barbed wire fences, watch guard houses, and spray repellents, have been introduced (Yamagawa et al. 2023). However, fences alone have limitations, as they are prone to breakage due to fallen trees, holes caused by bearded pigs, and monkey (*Macaca nemestrina* Linnaeus, 1766) attacks that cannot be stopped by fencing (Yamagawa et al. 2023). Managing costs based on mammal density levels is crucial to minimizing browsing damage and allocating control measures according to financial capabilities. Thus, this study is a pilot model to link wildlife pest behavior with human disturbances and assess browsing damage on seven taxa in a trial plot near a roadside adjacent to an oil palm estate and secondary forest within the Lungmanis FR. This study aims to bridge the knowledge gap between browsing damage at an early stage and its post-survival effect on the growth performance of selected tree plantation species. Seven fast-growing commercial species were trialed, with two planted within fences. The study seeks to address three research questions based on two-time points: i) Which species experience high browsing intensity based on mortality rate and Severity Index? ii) Is there a significant difference in browsing intensity between planted taxa in fenced and non-fenced subplots? Moreover, iii) In this study, Do wildlife pests exhibit behavioral patterns that might influence the health, survival, and Post-Survival Indexes of planted taxa within the Randomized Complete Block Design (RCBD) plot setup? Additionally, the report includes data on recorded pests as a criterion for forest plantation management.

MATERIALS AND METHODS

Study area

The study was conducted in October 2020 at Kolapis A, Lungmanis FR., Beluran (coordinates N5.7919; E117.6710). The Lungmanis FR, Sabah, Malaysia, is a Class VI (Virgin Jungle Reserve) covering approximately 6,735 ha (Figure 1). It consists of five sub-reserves and serves as an active research facility for tree improvement, plantation trials, agroforestry, and yield studies under the plantation program of the Forest Research Centre, Sabah Forestry Department. The topography of the study site (Kolapis block 45A) mainly comprises low hills and narrow alluvial flats, with an amplitude of 15-30 m above sea level and short slopes ranging from 5-15 degrees on the hills (Johnlee et al. 2017). Adjacent to the study site are secondary forests, disturbed lowland mixed dipterocarp forests, and oil palm estates (Suis et al. 2021). An aerial survey was conducted in November 2021, a year after the taxa establishment, using an Unmanned Aerial Vehicle (UAV) equipped with a Phantom 4 Pro (DJI, Shenzhen, China). High-resolution aerial imagery of the study site was captured and controlled using Map Pilot software (Figure 1).

Taxa trial and planting materials

The taxa trial plantation consisting of 1,372 individuals of fast-growing commercial species was established, covering a total area of 1.23 hectares. The trial followed an RCBD with four replications (28 sub-plots) of 7 × 7-tree plots spaced 3 meters apart. Seven taxa, namely Acra (*Acacia crassicarpa* A.Cunn. ex Benth., Fabaceae), Neom (*Neolamarckia cadamba* (Roxb.) Bosser, Rubiaceae), Falc (*Falcataria moluccana* (Miq.) Barneby & J.W.Grimes, Fabaceae), Term (*Terminalia copelandii* Elmer, Combretaceae), Epel (*Eucalyptus pellita* F.Muell., Myrtaceae), Smac (*Swietenia macrophylla* G.King, Meliaceae) and Khay (*Khaya ivorensis* A.Chev., Meliaceae), were evaluated (Table 1). Temporary barbed wire fences were installed to mitigate wildlife pest attacks. These fences, made from recycled stack poles of Bornean ironwood (*Eusideroxylon zwageri* Teijsm. & Binn.; 2" × 2" in size), were installed at the height of approximately 1.5 meters with a 15 cm gap (Figure 2.B). They were placed around two species (Neom and Falc), which were frequently preferred by mammals and prone to damage. Damage to the bark, twigs, and leaves of these species has been previously reported (Ismail and Jiwan 2015), which could potentially reduce their growth and survival. Well-hardened seedlings were selected from the Forest Research Centre (FRC) nursery, and aged about six months old. The details of the seed sources and provenances are shown in Table 1.

Table 1. Information on seed sources and plot setup for taxa trials

Species	Prov.	M-tree	Seed source	Sub-plot No.
Acra		10	SEP4522-SEP4530 (Sook, Keningau)	1, 9, 23, 25
Falc*	FMU14	9	FMU 14 (1) SEP 4509-SEP 4514 Tabin (2) SEP4543-4557 Sapulut	6, 8, 11, 13
Epel		10	SEP4466-4475 (Plot KB96/22) Beluran	2, 15, 18, 26
Khay		1	SEP 4542 (SSB Tawau)	3, 20, 21, 27
Neom*		10	Philippines (Gum-Gum RS) SEP4521, SEP4532-4541	5, 7, 12, 14
Smac	Solomon	10	Kolapis B, (KB85/13)	4$^{\pm}$,16, 19, 28$^{\pm}$
Term		10	unknown	10$^{\pm}$, 17, 22, 24

Note: Prov: Provenance; M-tree: Mother tree; FMU 14: Forest Management Unit 14; Abbr.: Abbreviation; RS: Research Station. *Barbed wire fences were installed for these subplots. ±Subplots no. 4, 10, and 28 were isolated from the main plot

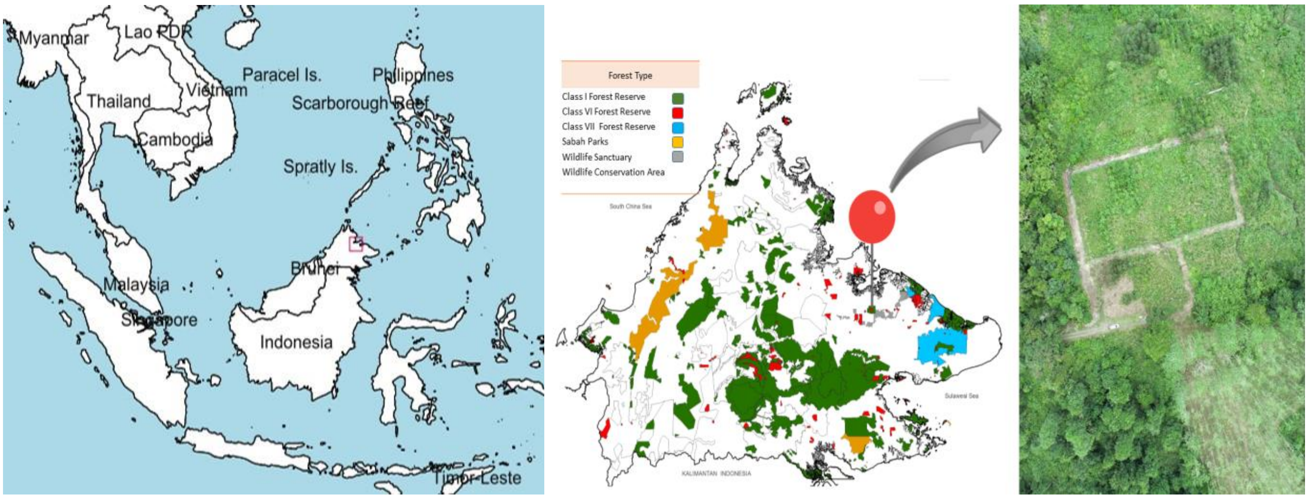

Figure 1. Location map and aerial image by UAV in the Lungmanis FR, Sabah, Malaysia

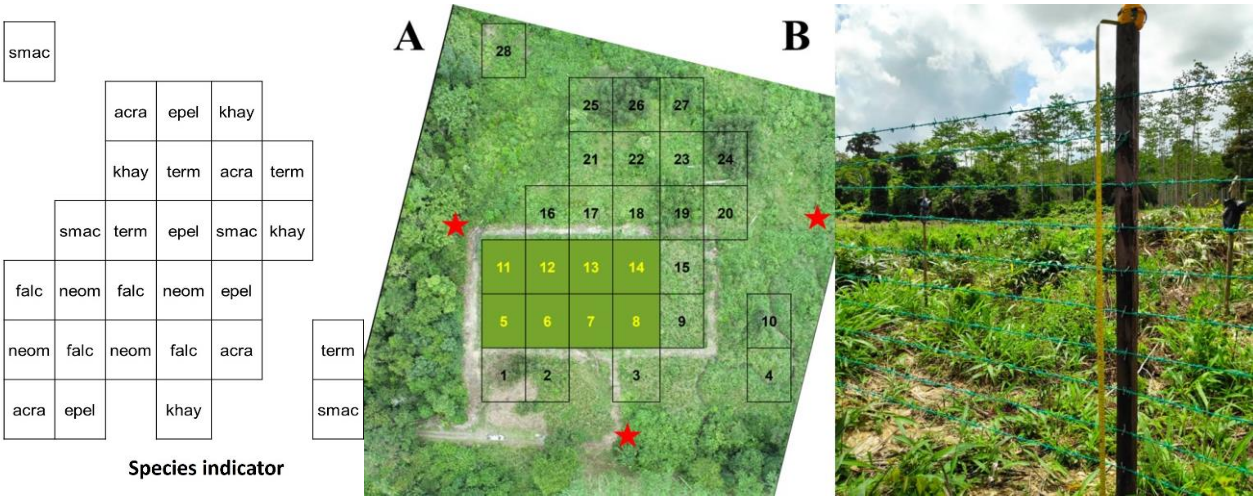

Figure 2. A. Plotted image depicting the taxa trial positioning sub-plot number; with B. Yellow font color indicating tree species that have been fenced as a physical barrier against wildlife pest attacks. Red stars refer to the placement of wildlife cameras by Suis et al. (2021), with the taxa legend according to the subplot placement shown on the left

The planting site was manually cleared by slashing prior to planting. The size of the planting hole was 30 cm in height, 20 cm in width, and 30 cm in depth, and planting was completed nearly at the end of the year to avoid seedling stress due to extreme conditions in the open surroundings. For the post-planting period, weeds were controlled by chemical spray using a mixture of Metsulfuron (3-5g/16L) and Glyphosate (220 mL/16L). Fertilizer was provided only once to the seedlings during the planting stage, using AGROBLEN (slow-release NPK fertilizer at ~5g/seedling), but no thinning or pruning was conducted.

Soil description: Rumidi (Soil association in Sabah)

It normally occurs on low hills and minor valley floors with slopes between 15 and 30 meters above sea level (masl). Soils are derived from mudstone and sandstone, which is a mixed colluvium. Rumidi soils are suitable for agricultural development. The soil profile is characterized by high levels of clay (subsoil) and low base (K, Ca, Mg) saturation. The topsoil level contains a thin amount of organic carbon and is classified as Alisols (Inagaki and Titin 2009).

Climatic and soil condition

During the planting period from October 2020 to December 2021, the taxa trial site experienced maximum temperatures ranging from 27°C to 30°C, with the warmest temperatures recorded in August. Conversely, the minimum temperatures fluctuated from 19°C to 20°C, reflecting a relatively consistent minimum temperature range. In terms of rainfall, the study recorded varying amounts throughout the year. The wettest months were January and May, with 395.32 mm and 350.71 mm of rainfall, respectively. In contrast, the driest months were February and March, receiving 199.46 mm and 155.34 mm of rainfall, respectively. Rainfall amounts appeared to be higher during the beginning and middle of the study period and slightly lower towards the end, with September having 221.67 mm of rainfall. Temperature and rainfall data were obtained from www.worldweatheronline.com. A soil profile survey conducted by the Japan International Research Center for Agricultural Sciences (JIRCAS) in collaboration with the Sabah Forestry Department in 2007 reported that the study site has low-nutrient soil with high acidity (pH level = 4.71) and erodible soil (Inagaki and Titin 2009). Therefore, it is recommended to apply a soil conditioner to the surface soil before planting, given these soil conditions. However, in this study, no soil conditioner was applied to the planting site.

Data collection and analysis

Data collection occurred at two time points: within the first three months (t1) on 21 January 2021 and after one year (t2) on 8 December 2021. Growth performance metrics such as Diameter at Breast Height (DBH) and height were measured for all individuals. Simultaneously, binary indexes were used to determine survival rates (H-Index) and pest infestation (Pest-Index), with field photos taken for pest identification. Browsing damage intensity by wildlife pests was assessed using the severity levels (S-Index) based on five categories outlined in Table 3, providing an overview of severity descriptions of observed damage for each tree species. Additionally, a post-survival evaluation (PS-Index) was introduced to evaluate the inflicted damages within the subplots, using seven descriptions provided in Table 4. Data from t1 and t2 were compared to assess any associations or significant differences between the applied indexes and taxa, as well as between indexes and plot setups. This aimed to understand species recovery after wildlife pest attacks, growth performance, species adaptation, and browsing intensity disparities among trees in fenced and non-fenced areas or isolated subplots. The selected taxa and their subplot numbers were abbreviated (Table 1; Figure 2).

Basic data processing and descriptive statistics were performed using MS Excel (MS Office Professional Plus 2019). All parameters were assessed for normality with the Shapiro-Wilk test using the PAST 3.22 program (Hammer et al. 2001). Further statistical tests were performed using the DATAtab Statistics Calculator (DATAtab e.U., Graz, Austria) (DATAtab Team. 2022) and Sigmaplot version 14 (Systat Software Inc., 2017). All data were tested using non-parametric statistical analysis using the Wilcoxon Signed-Rank test for S-Index and height, proportion test for H-Index, Kruskas-Wallis test, and post-hoc Dunn-Bonferroni test for the pairwise group on comparing taxa or plot-setup with selected indexes (Table 2).

Table 2. Type of data and statistical analysis were performed

Index	Type of data (t1, t2)	Statistical analysis
Health Index (H-Index)	Binary	Proportion test, z
Severity Index (S-Index)	Ordinal categorical	Kruskas-wallis, Wilcoxon Signed-Rank test, Dunn-Bonferoni test within the group
Performance in height, m	Metric nominal	Kruskas-wallis, Wilcoxon Signed-Rank test, Dunn-Bonferoni test within the group
Post Index (PS-Index)	Metric nominal	Descriptive statistic
Pest Index	Binary	Descriptive statistic

Table 3. Severity Index (S-Index)

Value	S-Index	Description
4	Low damage to none	No height loss, a tree considered as healthy
3	Moderate damage	Moderate damage occurs to growth (tree height loss between 5%-25%) or without primary and is likely to produce lateral shoots (forking)
2	High damage	Heavy damage occurs to growth (tree height loss between 25%-50%) or without primary shoot and lateral branches
1	Severe damage	Severe damage occurs to growth (tree height loss between 50%-70%) or without Terminal shoots and branches resulting from broken stems by wildlife pests
0	Death	Death

Table 4. Post-Survival Index (PS-Index)

Observation index	Description
1. Waterlogged	Lower areas are often flooded, causing dieback in planted trees.
2. Broken	The main stem is broken due to wildlife attacks, and recovery to its initial form is unlikely.
3. Shooting	Recovery of new shoots was grown in response to wildlife browsing.
4. Stunted	Dwarf tree or loss of vigor due to abiotic factor
5. Tilted	Leaning trees due to various possible factors, e.g., mechanical damage, root issues, wind exposure, infection, or disease.
6. Forking	Refers to the development of multiple stems or branches were emerge from a single point on a tree.
7. Death stump	refers to the remaining base or lower portion of a tree that has been removed or is dead.

RESULTS AND DISCUSSION

Taxa performance

Health index (H-Index)

Table 5 compares the mortality rates and H-Index changes over time (t1-t2) for different taxa (Acra, Epel, Khay, Smac, Neom, Falc, and Term), with each taxon initially having 196 individuals. The data reveals that taxa in fenced plots, particularly Neom and Falc, experienced the highest mortality rates of -34.18% and -41.33%, respectively. In contrast, taxa in open plots, such as Smac, had the lowest mortality rate at -5.61%. All taxa showed a decline in the H-Index from t1 to t2, correlating with their respective mortality rates. Interestingly, the results showed that fenced plots were associated with higher mortality rates compared to open plots (Figure 3).

Significant declines were observed for several taxa based on the H-Index analysis (Table 6.A). Khay showed a notable decrease in survival rate, indicating a significant decline (z = 3.224; p-value = 0.001). Falc faced a marked reduction in survival, highlighting one of the lowest survival rates (z = 6.236; p-value = 0.001). Neom also experienced a significant decline, showing increased susceptibility to survival challenges (z = 2.719; p-value = 0.001). In contrast, Acra and Term showed non-significant decreases, maintaining relatively higher survival rates over the year. Smac demonstrated a slight but significant reduction in survival (z = 2.178; p-value = 0.001). Similarly, Epel showed a significant reduction (z = 2.515; p-value = 0.001), although it remains one of the species with relatively high survival. Overall, all taxa except for Acra and Term experienced a statistically significant decrease in numbers after a year (Table 6.A).

Severity Index (S-Index)

The S-Index analysis showed the damage levels of the tree species based on index performance after a year (Table 6.B; Figure 4). Both Falc and Neom were categorized under the 'Severe damage' index, recording significant decreases in performance with the lowest mean S-Index with Falc (z = 9.535, p-value = 0.01, S-Index = 0.9±0.85) and Neom (z = 3.25, p-value = 0.01, S-Index = 1.16±1.06). Khay recorded a significant decrease in performance (z = 4.664, p-value = 0.01), with S-Index mean values dropping from 3.69±0.8 to 3.24±1.27. Conversely, Term showed a significant improvement in index performance (z = 2.224, p-value = 0.01), with S-Index mean values increasing to 2.21±1.1 at t2.

Other taxa, the like of Acra, Smac, and Epel, showed no significant changes in S-Index mean values and remained between 'moderate' and 'high damage' index categories. This suggests that some species can tolerate early predation by wildlife pests over time. Falc and Neom highlight the need for absolute protection from wildlife predation during the early planting phase due to their poor recovery rates. Post-hoc analysis using the Dunn-Bonferroni test indicated statistically significant differences in all pairwise group comparisons, except for Acra-Epel, Epel-Smac, Acra-Khay, and Falc-Neom (Table 5.A; S-Index). This suggests that these taxa (Acra, Epel, Khay, and Smac) have relatively higher mean S-Index values over the ongoing impact of wildlife pests after one year. Khay has been able to consistently withstand the pressure from browsing damage, while Neom and Falc experienced significant damage intensity.

Performance in height, m

Table 5.B underscores the height performance after a year, indicating significant increases in height for Acra and Epel recorded. Acra's height increased from 0.55 m to 1.12 m (z = 6.101, p-value = 0.01; Table 6.C), and Epel's height increased from 0.82 m to 1.54 m (z = 4.539, p-value = 0.01; Table 6.C). Both species initially faced moderate wildlife pest damage but demonstrated a significant recovery in height. Khay and Smac also displayed significant increases in height, with Khay (z = 7.037, p-value = 0.01) and Smac (z = 7.464, p-value = 0.01). Term exhibited a notable height increase (z = 3.726, p-value = 0.01), while Neom and Falc did not show any significant height increases. Both Neom and Falc corresponded to the S-Index and were placed under "severe damage". The Kruskal-Wallis test showed significant variation in height growth among species after one year ($\chi2(6)$ = 210.66, p-value = 0.001). Species like Epel and Acra showed their ability to recover and grow (Figure 5), while both Neom and Falc were severely impacted by early browsing damage, thus suggesting their limited growth due to the damage intensity. However, some resilient species like Term and Smac still managed to grow significantly over time.

Plot setup

Plot configuration analyzed the influence of the H-Index and damage intensity (S-Index) of planted trees over time (Table 7). Initially (t1), the fenced plots (A) had an 82.4% survival rate but experienced considerable damage, reflected by a relatively low mean S-Index (1.99±1.23). In contrast, isolated plots (B), mainly housing Smac and Term, achieved a 100% survival rate with moderate damage (S-Index = 2.33±0.83). Plot C, an isolated single plot at the forest edge, showed a 93.90% survival rate and minimal damage (S-Index = 3.41±1.04). The non-fenced plots (D), accommodating an extensive setup with 833 planted trees spanning multiple species, maintained a 94.00% survival rate with moderate damage (S-Index = 3.04±1.24).

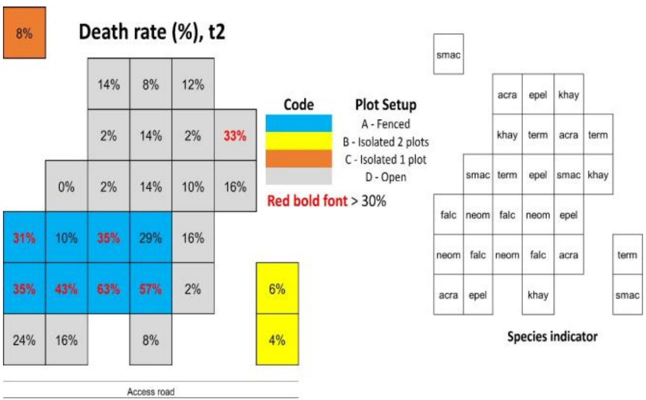

Figure 3. Taxa trial plot setup details and death rates (%) after one year

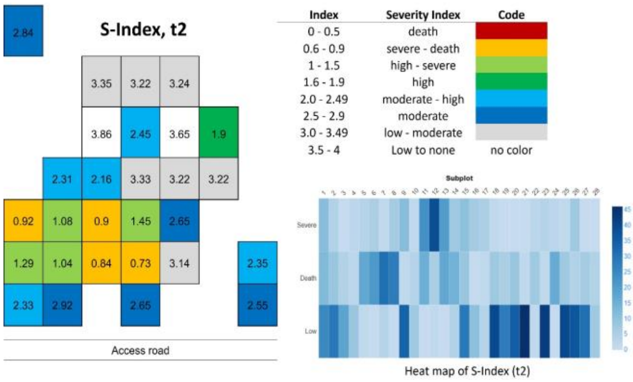

Figure 4. Taxa trial map on S-Index data after one year

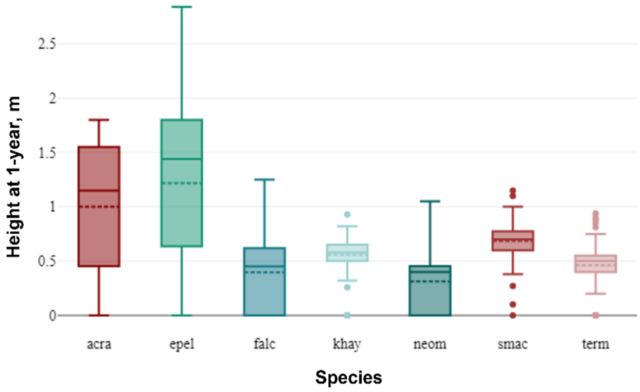

Figure 5. Bar chart on 1-year height (*t2*) for each species

Table 5. Information of taxa according to indexes and height, for two time points (t1 and t2)

Info / Taxa	Acra	Epel	Khay	Smac	Neom	Falc	Term
Plot configuration:	Open	Open	Open	Open	Fenced	Fenced	Open
No. of seedlings planted:	196	196	196	196	196	196	196
No. of subplot*	4	4	4	4	4	4	4
A. Indexes							
H-Index (1), t1	180	184	192	193	153	170	178
H-Index (1), t2	175	169	177	185	129	115	169
Mortality rate, t1-t2 (%):	-10.71%	-13.78%	-9.69%	-5.61%	-34.18%	-41.33%	-13.78%
**S-Index, t1	3.21±1.41^{ab}	3.1±1.43^{ab}	3.69±0.8^{c}	2.77±0.86^{d}	1.56±1.22^{e}	2.42±1.09^{f}	2.14±0.82^{e}
**S-Index, t2	3.12±1.5^{a}	3.03±1.55^{b}	3.24±1.27^{b}	2.73±1.08^{ab}	1.16±1.06^{c}	0.9±0.85^{c}	2.21±1.1^{d}
S-Index damage category, t1 to t2:	≤ Moderate	≤ Moderate	≤ Low to ≤ Moderate	Moderate to > high	High to Severe	High to Severe	≤ High
B. Tree height, m							
Mean of height, t1:	0.55± 0.12	0.82± 0.13	0.4± 0.08	0.51± 0.08	0.31± 0.07	0.46± 0.09	0.41± 0.09
Mean of height, t2:	1.12± 0.52	1.54± 0.49	0.59± 0.11	0.69± 0.16	0.45± 0.13	0.59± 0.22	0.52± 0.13

Note: * Number of subplots: Consist of 49 individuals/subplot; ** Dunn-Bonferroni test indicated by the same letter within each S-Index parameter do not differ significantly; p-value: 0.05. Data Mean±Standard deviation (Std.)

Table 6. Statistical analysis of taxa according to indexes and height at two time points (t1 and t2)

Taxa	t1	t2	prop. t1	prop. t2	z	Index performance
A. Proportion test for H-Index= 1 (alive)						
Acra	180	175	0.918	0.893	0.864	No significant
Epel	184	169	0.939	0.862	2.515*	Significant decrease
Khay	192	177	0.98	0.903	3.224*	Significant decrease
Smac	193	185	0.985	0.944	2.178*	Significant decrease
Neom	153	129	0.781	0.658	2.719*	Significant decrease
Falc	170	115	0.867	0.587	6.236*	Significant decrease
Term	178	169	0.908	0.862	1.426	No significant
B. Wilcoxon Signed-Rank test for S-Index						
Acra	3.21±1.41	3.12±1.5	4	4	0.992	No significant
Epel	3.1±1.43	3.03±1.55	4	4	0.891	No significant
Khay	3.69±0.8	3.24±1.27	4	4	4.664*	Significant decrease
Smac	2.77±0.86	2.73±1.08	3	3	0.095	No significant
Neom	1.56±1.22	1.16±1.06	1	1	3.250*	Significant decrease
Falc	2.42±1.09	0.9±0.85	3	1	9.535*	Significant decrease
Term	2.14±0.82	2.21±1.1	2	2	2.224*	Significant increase
C. Wilcoxon Signed-Rank test for Height, m						
Acra	0.55± 0.12	1.12± 0.52	0.53	1.15	6.101*	Significant increase
Epel	0.82± 0.13	1.54± 0.49	0.815	1.44	4.539*	Significant increase
Khay	0.4± 0.08	0.59± 0.11	0.4	0.58	7.037*	Significant increase
Smac	0.51± 0.08	0.69± 0.16	0.505	0.7	7.464*	Significant increase
Neom	0.31± 0.07	0.45± 0.13	0.32	0.4	0.254	No significant growth
Falc	0.46± 0.09	0.59± 0.22	0.46	0.45	1.598	No significant growth
Term	0.41± 0.09	0.52± 0.13	0.41	0.5	3.726*	Significant increase

Note: * p-value is statistically significant <0.01; med.t1: median on 3-month; med.t2: median on 1-year; z: Z-score

Table 7. Details and statistical analysis of plot setup according to indexes

Plot setup	A	B	C	D
Plot description	Fenced plots	Isolated 2 plots	Isolated 1 plot	Open plot
No. of Subplots	8	2	1	17
No. of planted trees	392	98	49	833
Acra				196
Epel				196
Falc	196			
Khay				196
Neom	196			
Smac		49	49	98
Term		49		147
A. 3-month, t1				
(%) H-Index= 1	82.4%	100.0%	93.9%	94.0%
Mean Rank S-Index	797.89	525.04	462.12	910.77
Mean of S-Index	1.99±1.23	2.33±0.83	3.41±1.04	3.04±1.24
Dunn-Bonferroni test:	The pairwise group comparisons of D-B, D-A, B-C, and A-C are significantly different. Adj. p-value= 0.05			
B. 1-year, t2				
(%) H-Index= 1	62.50%	88.70%	91.60%	87.90%
Mean Rank S-Index	353.77	687.19	777.82	837.63
Mean of S-Index	1.03±0.97	2.45±0.96	2.84±0.96	2.92±1.41
Dunn-Bonferroni test:	The pairwise group comparisons of D-B, D-A, B-A, and A-C are significantly different. Adj. p-value= 0.05			
C. Wilcoxon Test on S-Index (t1, t2), *Z*	9.7887*	1.9762*	2.7989*	2.2245*

Note: * p-value is statistically significant <0.05

At t2, the fenced plots (A) experienced a sharp decline in survival rate to 62.5%, although damage intensity decreased (S-Index = 1.03±0.97). The isolated plots (B) experienced a drop in survival to 88.7%, with a slight increase in damage (S-Index = 2.45±0.96). Plot C had a similar trend, with a 91.6% survival rate and a reduced S-Index (2.84±0.96). The non-fenced plots (D) maintained an 87.9% survival rate, with slightly lower damage (S-Index = 2.92±1.41). The Kruskal-Wallis test confirmed significant differences in the S-Index across plot setups at both t1 (H(3) = 241.45, p = 0.001) and t2 (H(4) = 441.63, p = 0.001). Post-hoc analysis using the Dunn-Bonferroni test revealed significant differences in browsing intensity at t2, particularly between plot pairs: D-B, D-A, B-A, and A-C.

These results suggest that physical barriers in fenced plots (A) were insufficient to protect species like Neom and Falc from wildlife browsing. The non-fenced plot (D), containing a mix of species (Acra, Epel, Khay, Smac, and Term), showed variability in survival rates, likely due to differences in species susceptibility to wildlife activity. Plot C, isolated with 49 Smac trees, demonstrated the least damage at t1 (S-Index = 3.41±1.04), suggesting Smac's resistance to wildlife browsing. The Wilcoxon signed-rank test further supported this conclusion (z = 2.7989, p = 0.001; Table 7.C). Similarly, Plot B, isolated and planted with Smac and Term, exhibited moderate damage levels over time (S-Index at t1 = 2.33±0.83, t2 = 2.45±0.96), potentially due to its location near an access road, which may have deterred wildlife (Figure 4).

Post-Survival Index

A total of 646 trees out of 912 trees reportedly alive after one year (t2) was recorded in for Post-Survival Index. This assessment identified seven distinct post-survival conditions (Table 8). Among these, the "Shooting" index was by far the most prevalent, accounting for 81.3% of all recorded issues across all taxa and plot setups. The taxa most affected by this index were Term (157 trees), followed by Neom (115 trees), Smac (108 trees), and Falc (91 trees). Index "Forking" was commonly recorded in hardwood species like Smac and Khay, where multiple shoots regenerated, accounting for 4.8% of the total issues observed across all plots (Table 8; Figure S1). Index "Waterlogged" was mostly recorded for Acra with 18 trees at subplot 1 (flooded area beside a stream), leading to dieback and accounting for 4% of the total issues observed across all plots (Figure 6). Both the "Tilted" and "Broken" indexes, constituting 2.3%, were observed in Acra, Epel, and Khay, likely due to external factors such as monkey activity and bearded pig attacks. Finally, the "Death stump" index, accounting for 2% of the total issues, was recorded for a combination of Epel and Term trees.

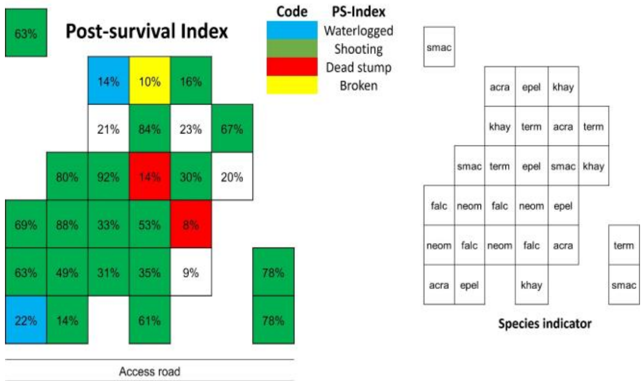

Figure 6. Information on the taxa trial map based on Post-Survival Index for every sub-plot

Figure S1. Post-Survival Index. A. Dead stump - *Neolamarkia cadamba,* B. Forking - *Swietenia macrophylla,* C. Multiple shoots - *Terminalia copelandii,* D. Tilted -exposed root system of *Terminalia copelandii* at subplot 22, E. Broken - *Acacia crassicarpa,* F. Stunted - *Falcataria moluccana,* G. Waterlogged subplot 1, H. Stunted -*Khaya ivorensis,* I. Broken stem of *Eucalyptus pellita*

Plot configuration

Both open Plot D and fenced Plot A had similar numbers of trees affected by the "Shooting" index, with 212 and 206 trees, respectively, indicating no significant differences in post-survival between these configurations. In Plot A, where fencing was used for two taxa (Falc, Neom), 206 trees exhibited new lateral shoots after the main shoots were eaten (Table 9). This correlates with the low S-Index values observed in Plot A at t1 and t2, suggesting that fencing was not fully effective in deterring wildlife pests. In terms of post-survival percentages, Term showed the highest percentage at 25.1%, followed by Smac (19.8%), Neom (17.8%), Falc (16.3%), Khay (8.7%), Acra (6.8%), and Epel (5.6%). These findings highlight how different taxa responded to wildlife pest pressure and adapted to browsing conditions.

Pest index

The Pest Index (Table 10) refers to the infestation rates of various species within the taxa trial plantation. The table uses binary data to indicate whether each species is infested (1) or shows no signs of infestation (0) to the total number of trees for each species. Neom stands out with the highest infestation rate at 23.5% by recorded *Arthoschista hilaralis* (Walker, 1859), while Falc recorded no signs of infestation. Acra had a 10.2% infestation rate caused by *Macrotermes gilvus* (Hagen, 1858), indicating a significant pest problem that needs to be addressed. Smac had the lowest infestation rate at 0.5% despite being susceptible to multiple pests like *Hypsipyla robusta* (Moore, 1886) and *Pagodiella* sp. Other species like Khay, Epel, and Term had relatively lower infestation rates, ranging from 1.5% to 3.1%. Khay, infested by *Cossus chloratus* (Swinhoe, 1892), showed a 1.5% infestation rate, while Epel, affected by *Hypomeces squamosus* (Fabricius, 1792), had a 2.6% rate. Term experienced a 3.1% infestation rate due to *Pagodiella hekmeyeri* (Heylaerts, 1885) (Figure S2).

These rates suggest a moderate susceptibility to pests, and the overall infestation rate for all species combined was 5.9%, underscoring the risk of pests in tree plantation management. When examining the impact on the H-Index (survival rate), it resulted that species with higher infestation rates, such as Neom at 23.5%, tend to experience reduced survival rates. The Pest-infested trees are often more vulnerable to wildlife browsing, potentially leading to a higher H-Index and suffering more severe damage due to increased wildlife activity (S-Index). In essence, there appears to be a positive relationship between the Pest Index score and both the H-Index and S-Index. Higher infestation rates tend to coincide with lower survival rates and elevated browsing intensity. However, it's important to note that Falc, despite its low infestation rate, exhibited low H-Index and S-Index values. Therefore, defoliating pests are not a significant factor for the taxa trial species in causing mortality in the early stages.

Table 8. Descriptive information on taxon according to Post-Survival Index

PS-Index/Taxon	Acra	Epel	Falc	Khay	Neom	Smac	Term
Broken	8	5	0	2	0	0	0
Stunted	3	4	10	2	0	1	3
Tilted	8	5	0	2	0	0	0
Forking	2	2	0	9	0	18	0
Shooting	5	9	91	40	115	108	157
Waterlogged	18	2	4	1	0	1	0
Death stump	0	11	0	0	0	0	2
Total	44	36	105	56	115	128	162

Table 9. Descriptive information on plot setup according to Post-Survival Index

PS-Index/Plot setup	D	B	A	C	Total
Waterlogged	21	1	4	0	26
Broken	15	0	0	0	15
Shooting	212	76	206	31	525
Stunted	7	4	10	0	21
Tilted	15	0	0	0	15
Forking	30	1	0	0	31
Dead stump	11	2	0	0	13

Table 10. Pest-Index on taxa (1 = Infested; 0 = No sign of infestation)

Species	0	1	%	Recorded pest
Acra	176	20	10.20%	*Macrotermes gilvus*
Epel	191	5	2.60%	*Hypomeces squamosus*
Khay	193	3	1.50%	*Cossus chloratus*
Smac	195	1	0.50%	*Hypsipyla robusta, Pagodiella* sp.
Neom	150	46	23.50%	*Arthoschista hilaralis*
Falc	196	0	0.00%	-
Term	190	6	3.10%	*Pagodiella hekmeyeri*
Total	1291	81	5.90%	

Table 11. Taxa mortality, H-Index, undesirable forms, and economic losses

Parameters	Acra	Epel	Falc	Khay	Neom	Smac	Term
Mortality rate out of 196 planted trees (t2)	10.7%	13.8%	41.3%	9.7%	34.2%	5.6%	13.8%
H-Index, 1 = survived tree, (t2)	175	169	115	177	129	185	169
Undesirable form rate based on PS-Index%	25.1%	21.3%	91.3%	31.6%	89.1%	69.2%	95.9%
Estimated total economic loss by taxa	33.2%	32.1%	94.9%	38.3%	92.9%	70.9%	96.4%
Estimated number of tree loss by taxa	65	62	186	75	182	138	188

A B C D

Figure S2. Pest infestation and diseases. A. Seedlings unaffected by *Hemithyrsocera histrio*, showcasing *Khaya ivorensis*'s ability to withstand even serious-looking pests, B. Deer-damaged stems of *Neolamarckia cadamba* increase susceptibility to plant diseases, C. *Pagodiella* sp. was recorded on Swietenia macrophylla, is not a surprise since they are quite polyphagous, D. Leaf defoliator recorded on *Terminalia copelandii*

Projection on taxa loss

The study associates economic loss in taxa trials with the H-Index (survived trees), mortality rate, and undesirable form rate based on the post-survival impact (PS-Index). Table 11 shows Term, Falc and Neom have the highest economic losses at 96.4%, 94.9%, and 92.9%, respectively, when factoring in both the mortality rate and the undesirable form rate. However, it is noteworthy that Term had a significantly lower mortality rate of 13.8% compared to Falc and Neom, which had rates of 41.3% and 34.2%, respectively. Due to post survival index of wildlife browsing, Term recorded the highest undesirable form rate at 95.9%. When combined with the mortality rate, this resulted in Term having the highest overall economic loss at 96.4%.

Smac has the lowest mortality rate (5.6%) but high undesirable forms (69.2%) and a 70.9% taxa loss. Epel, Acra, and Khay performed well with low mortality rates (9.7%-13.8%), undesirable forms (21.3%-31.6%), and the lowest economic losses (32.1%-38.3%), indicating their robustness and adaptation to wildlife damage. This highlights the need for targeted wildlife pest management for Falc and Neom at the early planting stages to reduce mortality and undesirable form rates. Specialized deterrents, beyond conventional barbed wire fencing, are necessary, especially near forest reserves with high mammal densities. Epel, Acra, and Khay's strong performance suggests they are reliable choices for tree plantation programs. On a side note, most of the Acra were affected by mortality due to waterlogged conditions during the rainy season in subplot 1 (Figure S2). In contrast, *Terminalia* species, being water-tolerant (Marjenah and Putri 2017), are more adaptable to these conditions.

Discussion

Fencing as a mitigation measure: A limited deterrent

One intriguing finding of our study was that both open (D) and fenced (A) plots showed similar levels of the PS-Index on "Shooting," suggesting that fencing did not wholly deter wildlife from browsing on the shoots of planted trees at the study site. Traditionally, fencing serves as an effective measure to mitigate wildlife-induced damage in tree plantations by acting as a physical barrier. However, our findings suggest its effectiveness may vary, especially with certain species or under specific conditions. Suis et al. (2021) strongly confirmed the ineffectiveness of the fencing method deployed to guard susceptible taxa from wildlife pests. This is supported by recordings from wildlife cameras, which identified Sambar deer, pig-tailed macaques, and bearded pigs as significant browsers responsible for damaging newly planted seedlings at the study site. These animals play a significant role in the ineffectiveness of fences, as they may find ways to get over fences or migrate to other taxa in open fields in search of food. For example, Sambar deer are known for their agility and ability to jump over obstacles, including fencing. Monkeys can use their climbing abilities to find access points from above, and bearded pigs persist in seeking food sources by foraging (Pulsford et al. 2022; Xu et al. 2023). This advances our understanding of wildlife's significant adaptability and determination to access valuable food resources, even when faced with physical barriers. More importantly, it underscores the need to consider fences' design, height, and maintenance to achieve deterrence objectives, whether for long-term or temporary use. A short-term solution is to set up inexpensive temporary fences made of bamboo or recycled planks to protect seedling development during the early stages and sensitive regeneration phases. Installing electric fences is a compelling long-term method to minimize mammal attacks. However, the high setup costs may deter budget-constrained companies from adopting this approach. Improvisation or finding alternative deterrent methods, such as using spray repellents, devices for animal intrusion detection alarms, or manual monitoring by watch guards, is necessary to secure the plantation site fully. This highlights the importance of forest managers and policymakers adopting a multifaceted wildlife management approach. Therefore, they need to incorporate both physical barriers and an understanding of local wildlife's ecological behaviors and adaptability. These recommendations align with studies by Harwood and Nambiar (2014), Latham et al. (2017), and Kumar et al. (2020), who advocate for holistic and adaptive wildlife pest management methods in forest ecosystems and suggest their relevance for forest plantation.

Understanding wildlife-induced tree damage

The study conducted by Suis et al. (2021) revealed important findings about wildlife activity in Lungmanis Forest Reserve, recording 14 mammal species. Among these, 12 species were confirmed as pest mammals affecting the planted tree seedlings within the study site. Based on these findings, we can associate the damage inflicted on the taxa according to the indexes and the previous records from wildlife camera detection rates. Three wildlife cameras were strategically positioned near subplot-3, subplot-20, and subplot-11 and installed from 8th to 16th December 2020 (Figure 2). The results highlighted three significant browsers: Sambar deer, pig-tailed macaques, and bearded pigs. The highest camera detection rate was identified for pig-tailed macaques (40), followed by Sambar deer (14), bearded pigs (2), and the lesser mouse deer (Suis et al. 2021). These results correspond to the high mortality rates for Neom and Falc in fenced plots, which were severely browsed by Sambar deer, resulting in damage to the primary shoots, stems, and leaves within the 3 months (Figure S3).

Figure S3. S-Index. A. Moderate damage = moderate damage to growth (tree height loss between 5%-25%) or without primary shoots: A.1. *Swietenia macrophylla*, A.2. *Terminalia copelandii*, A.3. *Neolamarkia cadamba.* B. High damage = Heavy damage to growth (tree height loss between 25%-50%) or without primary shoot and lateral branches. B.1. *N. cadamba*, B.2. *T. copelandii*, B.3. *Falcataria moluccana.* C. Severe damage = Severe damage to growth (tree height loss between 50%-70%) or without Terminal shoot and branches, resulted from broken stems by wildlife pests: C.1. *F. moluccana,* C.2. *T. copelandii*, C.3. *N. cadamba*

When the final assessment was conducted after a year, it revealed that the PS-Index category on "Shooting" had increased for other taxa, namely Term, Smac, and Khay. This shows the desperation and activity of Sambar deer who continue to forage after they have completely depleted their preferred taxa, while Epel and Acra were least affected. Repeated browsing can lead to the regeneration of multiple shoots, a condition known as “Forking,” which is a highly undesirable trait for plantation managers due to the loss of stem volume and quality. Additionally, significant harm to the main stem by debarking and browsing on the palatable inner bark of grown trees can cause rot to the open wounds and create weak points that promote infestations by insect pests or pathogens, increasing the mortality risk (Syazwan et al. 2021; Ghelardini et al. 2022).

This corresponds to the study conducted by Ismail and Jiwan (2015), which found that the availability of palatable woody plants with high protein storage, such as legumes like Falc, influenced browsing preference for Samba dear. However, in this study, Acra, known for its nitrogen-fixing properties and high protein content, experienced minimal browsing from Sambar deer. This may be attributed to the presence of high levels of tannin compounds in Eucalyptus and Acacia species. Consuming these compounds at concentrations above five percent can potentially affect voluntary feed intake in animals and even cause mortality (Nawab et al. 2020). Similarly, the poisonous resinous damar (terpene) found in the dipterocarp family is also avoided by these animals (Ismail and Jiwan 2015).

Monkeys, particularly pig-tailed macaques, are recognized as distinct wildlife pests in the area. The study site attracts these groups due to its proximity to a forest reserve and an oil palm estate at the outer boundary. A study conducted by Ruppert et al. (2018) in Peninsular Malaysia concluded that macaques spend their daytime feeding and foraging in plantation areas but rest in the forest at night. At this study site, the macaques primarily foraged on the ground, but their other activities, such as climbing and rampaging, caused damage to the lateral shoots and branches of the planted taxa (Suis et al. 2021). This corresponds to the PS-Index category of "Broken" for taxa such as Acra, Epel, and Khay. However, minimal damage was recorded for these taxa due to their resilience and ability to recover, often leading to the regeneration of multiple shoots (forking).

Bearded pigs are among the mammal foragers that cause severe damage to the trees planted at this study site. Their foraging activities, primarily in search of earthworms, have a detrimental impact on taxa growth and survival rates due to depleted soil nutrients and damage to the rooting system (Chitwood et al. 2022). The PS-Index recorded for "Stunted" and "Tilted" shows evidence of reduced tree growth, tilted trees due to foraging and rooting movements, and subsequently, the mortality of "Dead stump" trees (Figure S4). Other smaller herbivores, such as mouse deer, porcupines, Malay civets, and plain tree shrews, also contribute to tree damage but to a lesser extent (Suis et al. 2021).

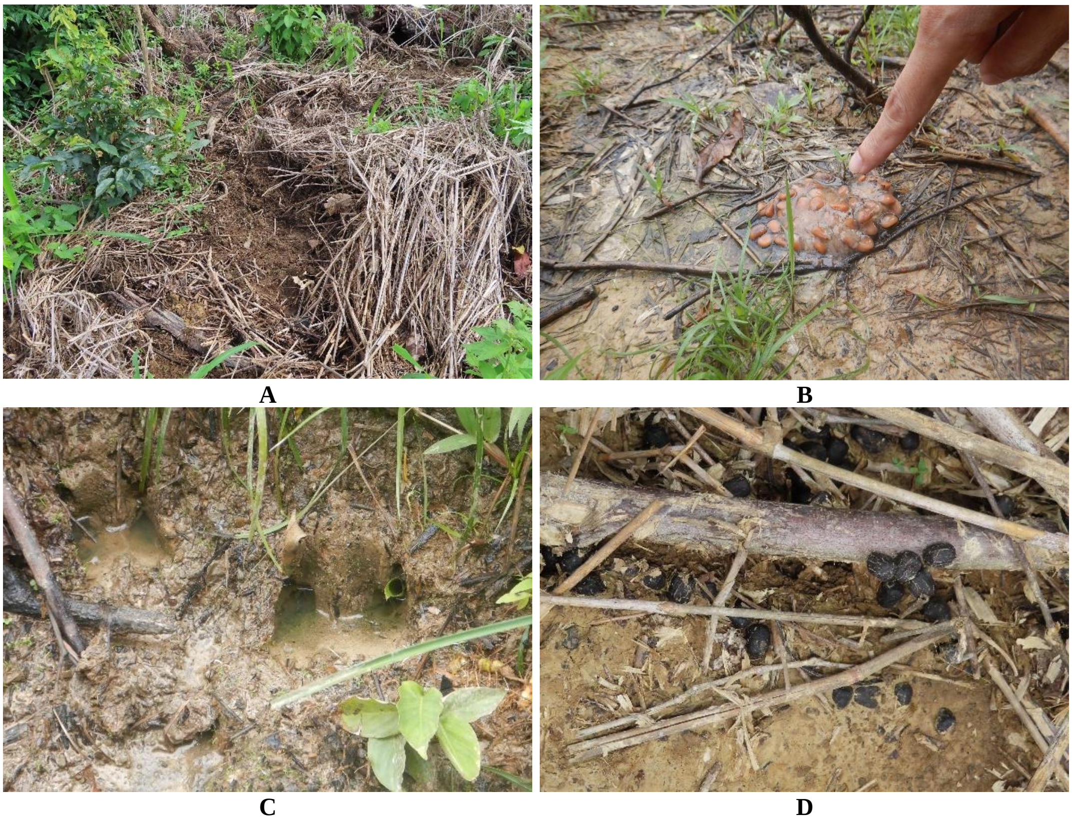

Figure S4. Wildlife footprints. A. Foraging activity by Bearded pig at Subplot 3, B. Civets’ spillover recorded at subplot 1, C. Deer footprints recorded at subplot 24, D. Deer feces recorded inside the fenced subplot

Figure S5. Staff inspecting a dead bearded pig suspected of ASF infection at the taxa trial on 19/02/2021

The specific impact of each wildlife species on the selected tree taxa can vary, influenced by factors like tree species, age, and local environmental conditions. Therefore, more studies on wildlife pest behavior and their roles in specific tree plantation species are needed to provide comprehensive insights and underscore the imperative need for proactive management approaches. To conclude our study on wildlife pest behavior in response to anthropogenic disturbances within Sabah's Lungmanis FR., we found that damage caused by mammal browsing may not be directly proportional to the population density of mammal species in the forest network, as suggested by Gaudry et al. (2022). This conclusion is supported by the small number of primary browsers recorded, namely sambar deer and bearded pigs (Suis et al. 2021). Additionally, the severe impact of the African Swine Fever (ASF) outbreak in 2021 (Ito et al. 2023), which massively reduced the bearded pig population in Sabah, along with evidence of a dead bearded pig recorded at the taxa trial (Kurz et al. 2023; Figure S5), still caused significant damage to the plantation taxa. These findings indicate that human impact factors, as suggested by Bersacola et al. (2019) and Laneng et al. (2021), beyond population density, contribute to browsing damage in this context.

Limitations of study

This study has identified key areas for improvement but also has limitations. The one-year duration may not capture long-term trends, underscoring the importance of extended monitoring. Additionally, the study on pests and diseases was constrained by insufficient data due to the length of the trial period. The study's focus on the Lungmanis Forest Reserve in Sabah limits comparisons of tree growth and browsing damages to other plantation sites. For future research, extending the monitoring period and collecting long-term data will highlight consistent effects of wildlife pest damage on tree populations, providing insights into survival and damage patterns in overgrowth stages. Exploring additional environmental variables such as topography and soil chemical properties across different locations will enhance our understanding on the taxa field performance.

Acknowledging the limitations of this research can improve our understanding of the impact of wildlife browsing and the adaptive capacity of taxa on early plantation forest clearance in Sabah. This includes species selection, environmental conditions, and protective measures for research plots in natural reserves like Lungmanis FR. Therefore, a collaborative effort between the Sabah Wildlife Department and the Sabah Forestry Department is essential to address the issue of mammal browsing in forest plantation research plots. These research plots are important departmental assets and serve as demonstration sites to showcase tree plantation models that support the State's wood industry in pursuing the sustainable production of timber resources.

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