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IMPACT OF ROAD CONSTRUCTION ON TREE DIVERSITY AND FOREST STRUCTURE IN AN INTACT BORNEAN MIXED DIPTEROCARP FOREST

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ABSTRACT
IDERIS, N. K. H., JAAFAR, S. MD. & SUKRI, R. S. 2025. Impact of road construction on tree diversity and forest structure in an intact Bornean mixed dipterocarp forest. *Reinwardtia* 24(1): 1–15. — Road construction has previously been shown to negatively impact biodiversity and is an urgent threat to Bornean tropical forests. We investigated changes in tree species diversity and forest structure of the Andulau Forest Reserve in Brunei Darussalam, following the construction of the Telisai-Lumut Highway. Within nine 20 × 20 m plots set up at varying distances from the forest edge where the road was located, we measured all trees ≥ 1 cm in diameter at breast height for their stem diameter, height and crown characteristics, and identified all trees ≥ 5 cm dbh. Although mean tree abundance and diversity between plots were similar, we detected significant differences in forest structure, particularly stem diameter, basal area, and crown characteristics. Plots closest to the road recorded the highest total tree species richness, although not significant, and contained a mixture of pioneer tree species and remnant interior forest species, while no pioneers were recorded in the interior forest plots. We documented the presence of high conservation value species, including three critically endangered species (*Gonystylus bancanus*, *Hopea micrantha,* and *Vatica venulosa*). Our work illustrates the potential impacts on forest structure from road construction and highlights the need for further studies to assess the long-term impacts on tree diversity and forest dynamics.

Key words: Brunei, edge effects, forest fragmentation, tree diversity conservation.

ABSTRAK
IDERIS, N. K. H, JAAFAR, S. MD. & SUKRI, R. S. 2025. *Reinwardtia* 24(1): 1–15. Dampak pembangunan jalan pada keanekaragaman pohon dan struktur hutan di hutan alami dan hutan campuran dipterokarpa Borneo. — Konstruksi jalan sebelumnya telah terbukti memiliki dampak negatif pada keanekaragaman tumbuhan dan merupakan ancaman besar bagi hutan tropis Borneo. Kami meneliti perubahan keragaman jenis pohon dan struktur hutan di Hutan Lindung Andulau di Brunei Darussalam, setelah pembangunan jalan raya Telisai-Lumut. Dalam sembilan plot berukuran 20 × 20 m yang didirikan pada jarak yang bervariasi dari tepi hutan tempat jalan raya berada, kami mengukur semua pohon ≥ 1 cm dbh untuk diameter batang, tinggi, dan karakteristik kanopi mereka, serta mengidentifikasi semua pohon ≥ 5 cm dbh. Meskipun kelimpahan dan keragaman rata-rata pohon antara plot serupa, kami mendeteksi perbedaan signifikan dalam struktur hutan, khususnya diameter batang, luas dasar, dan karakteristik kanopi. Plot yang terdekat dengan jalan tercatat mempunyai jumlah kekayaan jenis pohon tertinggi, meskipun tidak signifikan, dan terdiri dari campuran jenis pohon pelopor dan jenis hutan dalam yang tersisa, sementara tidak ada pohon pelopor yang tercatat di plot hutan dalam. Kami mendokumentasikan keberadaan jenis bernilai konservasi tinggi, termasuk tiga jenis yang sangat terancam punah (*Gonystylus bancanus*, *Hopea micrantha,* dan *Vatica venulosa*). Kajian kami menggambarkan potensi dampak pada struktur hutan akibat konstruksi jalan dan menyoroti perlunya penelitian lebih lanjut untuk menilai dampak jangka panjang pada keragaman pohon dan dinamika hutan.

Kata kunci: Brunei, efek tepi, fragmentasi hutan, konservasi keanekaragaman pohon.

INTRODUCTION

Tropical rain forests are the most species-rich forest type of all terrestrial ecosystems and are thought to support more than half of all plant and animal species (Primack & Corlett, 2005; Gaveau *et al*., 2016). Biodiversity loss in the tropics is rapidly increasing due to human activities (Benitez -Lopez *et al*., 2010; Clements *et al*., 2014), and the construction of roads has been identified as a major factor leading to increased deforestation in tropical forests (Alamgir *et al*., 2017).

There is substantial evidence of the negative effects of roads on biodiversity and ecosystems (Benitez-Lopez *et al*., 2010; Clements *et al*., 2014; Alamgir *et al*., 2020). Forests severely disturbed by road construction record lower average canopy heights and basal areas per hectare, and higher tree density and relative area of canopy gaps (Oliveira-Filho *et al*., 1997). Tree community structure and dynamics may be considerably altered (Laurance & Yensen, 1991), with increased mortality of canopy trees and a burst in recruitment and growth of lianas, shrubs, and smaller trees (Laurance & Yensen, 1991; Murcia, 1995). Edges caused by road constructions are humanly induced and often linear in shape (Coffin, 2007; Gaveau *et al*., 2019) thus increasing accessibility. Forest edges have different microhabitats than the interior intact forest (Seiler, 2001; Ries *et al*., 2004; Senior *et al*., 2018). Roadsides often act as early-successional habitats (Avon *et al*., 2010), offering more nutrient-rich, humid and higher light conditions than the forest interior, resulting in a higher abundance of pioneer and non-forest species (Avon *et al*., 2013). These conditions also increase exotic plants invasions (Hansen & Clevenger, 2005; Dobert *et al*., 2017; Waddell *et al*., 2020a; 2020b), with areas adjacent to roads more likely to be colonized by alien species due to greater propagule pressure and increased human activities (Cameron & Bayne, 2009; Zeng *et al*., 2011; Mungi *et al*., 2021).

Within Borneo, road constructions are an emerging threat to biodiversity and forest connectivity (Alamgir *et al*., 2017). Approximately 364,000 km^2 of roads have been constructed through the Malaysian states of Sabah and Sarawak (Bryan *et al*., 2013), and the construction of the Pan-Borneo Highway is expected to affect 32 protected areas, including habitats for threatened species (Alamgir *et al*., 2020). In Indonesian Borneo, planned and ongoing road construction and infrastructure projects are predicted to increase the accessibility of the majority of old-growth forests (Alamgir *et al*., 2019). In Brunei Darussalam, exotic *Acacia* species planted along roadsides have invaded and spread into degraded coastal heath forest habitats (Osunkoya *et al*., 2005; Jambul *et al*., 2020; Tuah *et al*., 2020; Jaafar *et al*., 2022a; 2022b).

Forests are more likely to be in peril where there are more roads, and thus long-term conservation strategies should consider ways to mitigate roads as drivers of deforestation and fragmentation (Freitas *et al*., 2010; Laurance *et al*., 2014). The Telisai-Lumut highway, constructed in 2010 close to the Andulau Forest Reserve in Brunei Darussalam has increased concerns about the negative effects of this road construction on the biodiversity of this protected area. We therefore studied the effects of the road construction on the tree communities at the Andulau Forest Reserve. In 2013, we investigated variations in tree abundance, species richness and diversity, as well as forest structure, from the then-newly constructed Telisai-Lumut highway into the Andulau Forest Reserve. Our study hypothesised that tree abundance and diversity would be significantly lowered closer to the highway and would remain high in intact forest further away from the highway. Additionally, we also hypothesised that forest structure, in terms of tree diameter at breast height, height and crown measurements, would be more heterogeneous with increasing distance from the highway and forest edge.

MATERIALS AND METHODS

Study sites

The study was conducted in Compartment 7 of the Andulau Forest Reserve (4°39’21.90” N, 114° 31’12.10” E; Fig. 1) in Sungai Liang, Kuala Belait, Brunei Darussalam. The study site was near one length of the Telisai-Lumut highway which is a dual carriageway (18.6 km long) constructed in February 2010. This study took place in 2013 while the construction work was still actively ongoing. Construction of this highway was completed in June 2016. A portion of the dual carriageway transverses and fragments some parts of the Andulau Forest Reserve (FR), which is currently included within Brunei Darussalam’s Heart of Borneo area. The Andulau FR consists primarily of mixed dipterocarp forests (Sukri *et al*., 2012) with pockets of heath forests (Anderson & Marsden, 1984; Davies & Becker, 1996) and has been selectively logged previously, but Compartment 7 was designated for research and remains unlogged (Davies & Becker, 1996; Sukri *et al*., 2012).

The current study was conducted in an area that showed heavy encroachment from the highway to the intact forest at the Andulau FR (4°39’21.90” N, 114°31’12.10” E). At this site, three parallel line transects were set up, each 300 m in length, and spaced more than 50 m apart. Along each transect, nine 20 × 20 m plots were set up: edge plots (*i.e.* plots 1, 2, and 3 located at *ca*. 30 m away from the forest edge), mid plots (*i.e.* plots 4, 5, and 6 located at 150 m away from the forest edge) and interior plots (*i.e.* plots 7, 8, and 9 located > 200 m away from the forest edge; Fig. 1). All plots were permanently marked with coloured PVC pipes at each corner and at the center. The distance between the forest edge and the road was 97.9 m and was determined using a laser range finder (Opti-Logic InSight 1000LH, Opti-Logic Corporation USA).

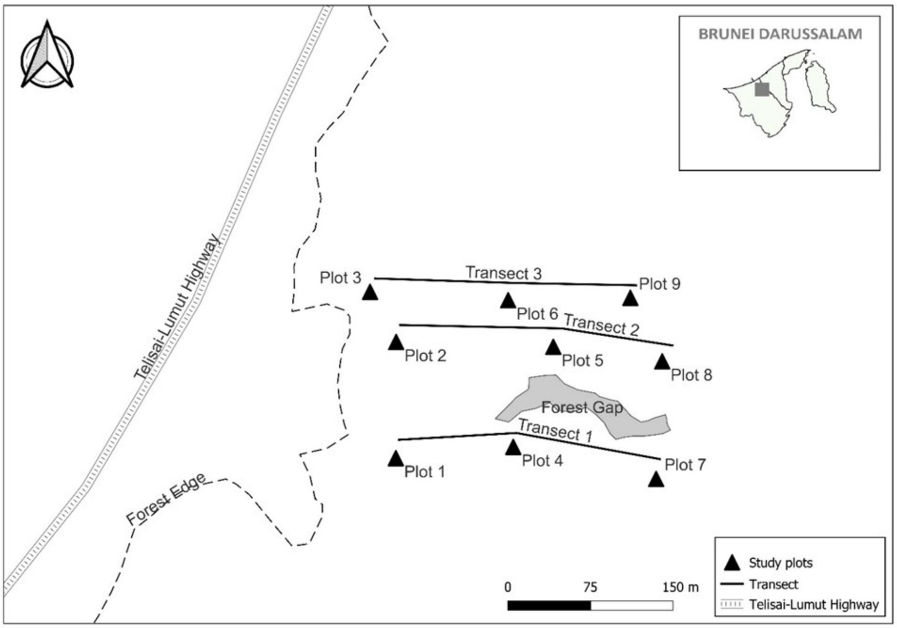

Fig. 1. Locations of the three transect lines and nine 20 × 20 m plots in compartment 7 of the Andulau Forest Reserve near the currently constructed Telisai-Lumut highway. Plot 1 to Plot 9 are the nine 20 × 20 m plots set up along the three transects. Inset map shows the location of the Andulau Forest Reserve within Brunei Darussalam.

Tree census and measurements of tree characteristics

All standing trees (excluding lianas and palms) of diameter at breast height (dbh) ≥ 1 cm within each 20 × 20 m plot were tagged and censused. Five measurements of tree characteristics were recorded for each tagged tree: dbh (cm), basal area (cm^2), tree height (m), tree bole height (m), crown depth (m), and crown width (m). Trees with dbh < 10 cm were considered small-sized, whereas trees with dbh ≥ 10 cm were considered large-sized (Turner, 2001; Lacerda *et al*., 2008; Din *et al*., 2015).

Tree bole height, crown depth, crown width, and crown height were only measured for trees of dbh ≥ 5 cm, following Condit (1998) and Din *et al*. (2015). All measurements of tree heights, tree bole height, crown depth and crown width were determined using a Laser Range Finder (Opti-Logic In-Sight 1000LH, Opti-Logic Corporation USA). Tree height was measured from the ground surface to the tip of the crown at its highest foliage point. Tree bole height is the distance between the ground and the point at which the first tree branch occurred, and crown depth was then calculated by subtracting the total tree height from the total bole height. Measurements of crown width were only taken for trees with dbh ≥ 5 cm. Four measurements (in m) were taken from the centre of the tree trunk to the crown edge in the four compass directions (N, E, S and W), and crown width was calculated as the average of these four distance measurements (Pretzsch *et al*., 2015).

Taxonomic identification focused only on trees with dbh ≥ 5 cm, which were identified to species level or according to morphospecies with the assistance of botany staff from the Brunei National Herbarium (BRUN) of the Brunei Forestry Department. Voucher specimens were collected and were brought to BRUN for identification against specimens currently at BRUN. Trees with dbh < 5 cm were not identified.

Data analysis

Four measures of tree diversity were determined: species richness, Shannon-Wiener index, Inverse Simpson's Index and evenness (Magurran *et al*., 2013). All diversity indices were calculated using the vegan package version 2.0-10 (Oksanen *et al*., 2013) in R version 3.0.3 (R Development Core Team, 2013). One-way ANOVA was used to determine significant differences between the three plot types for each diversity index, as well as stem abundance. Similarly, differences in tree characteristics (dbh, tree height, crown height, crown depth, crown width, and bole height) were analysed separately using one-way ANOVA. Significant differences detected from the one-way ANOVA analyses were further analysed using the Tukey HSD test. Assumptions of normality and homogeneity of variances for the one-way ANOVA tests were tested for each parameter, and if any violations were detected, the data were square -root or $\log_{10}$ transformed. All statistical analyses were conducted in R version 3.0.3 (R Development Core Team, 2013).

Table 1. Variation in stem abundance, tree structure measurements, abundance of juvenile trees (dbh ≤ 10 cm), and adult trees (dbh ≥ 10 cm) with increasing distance away from the forest edge: 30 m (edge plots), 150 m (mid plots), and 270 m (interior plots). Tree structure characteristics measured were diameter at breast height (dbh), basal area, total height, bole height, crown depth and crown width. Diameter breast height, basal area and tree height were measured for trees of dbh ≥ 1 cm, whereas, bole height, crown depth, crown width, and crown height were only measured for trees of dbh ≥ 5 cm. Different letters within columns of the same parameter mean significant differences (a or b).

	30 m	150 m	270 m	p-value
Stem abundance	335 ± 31.5	299 ± 37.2	352 ± 39.6	NS
Diameter at breast height (cm)	4.66 ± 0.23^{a}	4.03 ± 0.26^{b}	4.65 ± 0.28^{ab}	*
Basal area (cm^2)	59.0 ± 9.59^{a}	68.5 ± 28.8^{b}	71.5 ± 12.8^{ab}	*
Total height (m)	5.77 ± 0.16	4.74 ± 0.90	5.73 ± 0.18	NS
Bole height (m)	8.81 ± 0.29	9.61 ± 0.34	9.67 ± 0.37	NS
Crown depth (m)	3.43 ± 0.21^{a}	3.59 ± 0.16^{a}	4.28 ± 0.21^{b}	***
Crown width (m)	2.01 ± 0.07^{a}	2.34 ± 0.09^{b}	2.25 ± 0.09^{ab}	*
Abundance of juvenile trees	895	981	800	
Abundance of adult trees	104	73	97	

RESULTS

Variation in tree abundance in different DBH and height classes

A total of 2,950 trees were censused, with 999 trees recorded in the edge plots, 1,054 trees recorded in the mid plots and 897 trees recorded in the interior plots. Overall, most trees censused from all nine plots were small-sized (dbh ≤ 10 cm; n = 2,676 trees; Table 1), and of the height class 1−10 m (n = 2,545 trees). The abundance of small -sized trees was highest in the mid plots (n = 981 trees) and lowest in the interior plots (n = 800 trees) respectively. However, there were no significant differences in mean tree abundance between plots ($p > 0.05$; Table 1).

Variation in mean DBH, basal area, total tree height, bole height, crown depth and crown width

The mean dbh was significantly higher in the edge plots (dbh = 4.6 ± 0.2 cm) than in the mid plots (dbh = 4.0 ± 0.3 cm; $p < 0.05$; Table 1), but no significant differences were detected between edge plots and interior plots, and between mid plots and interior plots, respectively. The tree with the largest dbh recorded in the edge plots was *Dryobalanops beccarii* (Family Dipterocarpaceae; dbh = 87.2 cm), *Anthoshorea agami* (Family Dipterocarpaceae; dbh = 194 cm) for the mid plots and *Rubroshorea rubella* (Family Dipterocarpaceae; dbh = 88.9 cm) for the interior plots. The mean basal area was significantly higher in the mid plots (basal area = 68.5 ± 28.8 cm^2) than in the edge plots (basal area = 59.0 ± 9.6 cm^2; $p < 0.05$; Table 1), but no significant differences were detected between edge plots and interior plots, and between mid plots and interior plots, respectively.

The mean tree height for the mid plots (4.74 ± 0.09 m) was lower than in the edge plots (5.77 ± 0.16 m) and interior plots (5.73 ± 0.18 m; Table 1). However, these differences in tree height were not significant ($p > 0.05$). Similarly, there were no significant differences in mean bole height between the nine plots. The tallest tree recorded in the edge plots was *Rubroshorea scaberrima* (Dipterocarpaceae, height = 45 m), *Richetia angustifolia* (Family Dipterocarpaceae, height = 31 m) in the mid plots and *Rubroshorea curtisii* (Dipterocarpaceae, height = 37 m) in the interior plot.

Significant differences in crown depth were recorded between edge plots (crown depth = 3.43 ± 0.21 m; Table 1) and interior plots (crown depth = 4.28 ± 0.21 m; $p < 0.001$), as well as between mid plot and interior plots (crown depth = 3.59 ± 0.16 m vs. 4.28 ± 0.21 m; $p < 0.05$). Most trees recorded crown depths of 0 to 5 m. The mean crown width was significantly higher in mid plots (crown width = 2.34 ± 0.09 m) than edge plots (crown width = 2.01 ± 0.07 m; $p < 0.05$; Table 1) but did not differ between other plots. Most trees recorded crown widths of 1 to 2 m. A tree of *Dryobalanops beccarii* (Dipterocarpaceae) in one of the interior plots recorded the widest tree crown at 7.8 m.

Differences in species richness and diversity with increasing distance from the forest edge

A total of 53 families and 254 species of trees ≥ 5 cm dbh were recorded from the nine plots sampled (Appendix A). The most abundant family recorded overall was the family Dipterocarpaceae. The highest species richness was recorded at edge plots (n = 187 species), while mid- and interior

Table 2. Variation in tree diversity, determined using the Shannon index, evenness, inverse Simpson index and species richness, at increasing distances of 30 m, 150 m and 270 m away from the forest edge: 30 m (edge plots), 150 m (mid plots) and 270 m (interior plots), determined at α = 0.05.

Biodiversity indices	30 m	150 m	270 m	p-value
Shannon Index	2.54 ± 0.15	2.40 ± 0.12	2.43 ± 0.10	0.621
Evenness	0.96 ± 0.02	0.97 ± 0.01	0.98 ± 0.004	0.347
Inverse Simpson Index	12.8 ± 1.5	10.9 ± 1.3	11.2 ± 1.1	0.534
Mean species richness	15.6 ± 1.7	12.8 ± 1.4	12.7 ± 1.3	0.28

Table 3. Differences in tree species abundance with increasing distance from the forest edge, at edge plots (30 m), mid plots (150 m) and interior plots (270 m). Only the most abundant species (*i.e.* n ≥ 5 individuals) were included. Nine 20 m × 20 m plots were set up along three transect lines that were distanced at 50 m–100 m apart. Plots were distanced at 100 m–150 m apart.

Edge plots		Mid plots		Interior plots	
Richetia angustifolia	11	*Horsfieldia crassifolia*	11	*Richetia angustifolia*	8
Macaranga praestans	7	*Gaertnera junghuhniana*	10	*Dacryodes incurvata*	6
Mallotus griffithianus	6	*Dacryodes incurvata*	8	*Gonocaryum minus*	6
Rubroshorea mecistopteryx	6	*Parishia maingayi*	6	*Richetia laxa*	6
Microcos ossea	5	*Pentace laxiflora*	6	*Canarium littorale*	5
Rubroshorea macroptera	5	*Rubroshorea scaberrima*	6	*Kayea oblongifolia*	5
		Ardisia sp. 1	5	*Sterculia* sp. 1	5
		Dryobalanops beccarii	5		
		Litsea elliptica	5		
		Mallotus griffithianus	5		
		Norrisia major	5		

plots showed relatively similar species richness (n = 153 and n = 152 species, respectively). Despite this, mean species richness did not differ significantly between plots ($p > 0.05$, Table 2). Similarly, other measures of diversity (the Shannon and Inverse Simpson indices, and Evenness) were not significantly different between plots ($p > 0.05$, Table 2).

Edge plots recorded six species with an abundance of five or more individuals, while mid plots recorded 11 species and interior plots recorded seven species (Table 3). Of these, the most abundant tree species in the edge plots were *Richetia angustifolia* (Dipterocarpaceae, n = 11) and *Macaranga praestans* (Euphorbiaceae, n = seven). *Horsfieldia crassifolia* (Myristicaceae, n = 11 individuals) and *Gaertnera junghuhniana* (Rubiaceae, n = 10) were most abundant for the mid-plots while *Richetia angustifolia* (Dipterocarpaceae, n = eight) was most abundant in the interior plots (Table 3).

DISCUSSION

The effects of road construction on tree abundance

Our study did not detect significant differences in mean tree abundance between all three distances. This could be due to the small number of plots (n = three plots per distance) and the short period between the first clearing of the forest for road construction and the start of this study (*i.e.*, approximately three years). Edge effects are expected to result in increased tree abundance at the forest edge due to high light availability (Murcia, 1995; Oliveira-Filho *et al*., 1997), but edge effects typically take between two to eight decades to promote changes in the tree community composition and structure (Oliveira-Filho *et al*., 1997).

We recorded 999 total tree abundance near the edge (30 m distance) than in the interior areas (1,054 trees; 150 m and 897 trees; 270 m distances), though this was not statistically significant. It is likely that high tree mortality near the forest edge closest to the road construction occurred before our study. Additionally, constant disturbance from the road construction, such as landslips at the forest edge (Bruijnzeel *et al*., 2004), continued to affect the edge plots throughout our study as these plots were only distanced at least 30 m from the forest edge (Fig. 1). Increased wind exposure and heat stress at the forest edge may further increase tree mortality (Seiler, 2001; Laurance *et al*., 2007; Olupot, 2009), resulting in lower tree abundance at the edge plots. Notably, we observed that some of the bigger trees at our edge plots had died standing before the study, further indicating the potential adverse effects of road construction at the forest edge.

The effects of road construction on forest structure

There was a significantly lower mean dbh for trees in mid plots than those in edge plots, which is consistent with the higher abundance of small-sized trees in the mid plots. This difference may also be influenced by differences in tree species, as edge plots and interior plots contained more large-sized Dipterocarpaceae trees compared to the mid plots.

Although there were no significant differences in the mean tree heights between plots, there were significant differences in crown depth and crown width. Measures of crown width and depth differ between species and vary for individuals of the same species (Richards, 1996). The significant differences between crown depth and crown width of trees in between the edge plots and mid plots are likely due to differences in tree species present. Pioneer species, which were present in greater abundance in the edge plots, tend to have larger crown widths as they are usually open-branched to occupy larger space for maximal light capture (Ghazoul & Sheil, 2010). Additionally, the present study did not measure the crown widths and depths of trees with dbh < 5 cm which may also underestimate the total mean crown characteristic for all plots. The abundance of large trees of *Richetia angustifolia* (n = eight individuals) at the interior plots located 270 m from the edge may also contribute to the mean high mean crown width of these plots.

The effects of road construction on species richness and diversity

Our study did not detect significant differences in mean species richness and diversity between the edge, mid and interior plots, although the total number of species recorded was highest in the edge plots. Plant species richness has been shown to increase with road proximity (Avon *et al*., 2013; Mungi *et al*., 2021). Disturbance at roadsides increases canopy openness and light penetration, both of which provide opportunities for new recruitment and accelerate the growth of juvenile trees (Ghazoul & Sheil, 2010). However, higher diversity at forest edges tends to be associated with a higher presence of pioneer species compared to interior forest species (Goodale *et al*., 2012; Yano *et al*., 2021), which was consistent with our findings.

For trees ≥ 5 cm dbh, we found a higher abundance of pioneer species from the family Euphorbiaceae in the edge plots (n = 14 trees) and mid plots (n = 21 trees), compared to the interior plots (n = eight trees). This included disturbance indicator species such as *Macaranga* and *Mallotus* (Slik *et al*., 2003). We expected that the edge plots would have more tree species that are considered as shade intolerant or pioneer species (Ghazoul & Sheil, 2010; Najafi *et al*., 2012), due to higher light intensity which favours the fast growth of pioneer species (Goodale *et al*., 2012). However, our edge plots appeared to possess a mixture of both pioneer and non-pioneer species. A mix of generalist tree species with remnant trees of interior forest species is often found at the forest edge (Laurance *et al*., 2006). However, the high species richness at the forest edge typically decreases over time as more interior forest species die out to exposure to the harsh environment at the forest edge (Ghazoul & Sheil, 2010). Our observation at the study site is that most pioneer trees at the edge plots were likely juveniles (dbh < 5 cm). As we only identified trees ≥ 5 cm dbh, this may underestimate the total species richness in our plots.

Within the interior plots, no pioneer tree species were recorded. The higher abundance of interior forest species in plots at 270 m distance is indicative of the intact forest still found at distances further away from the road construction sites. *Richetia angustifolia* and *R. laxa* were found in abundance (more than five individuals; Table 3) here and for all distances in the study, the Family Dipterocarpaceae has the highest number of genera showing family dominance, consistent with the study site located in mixed dipterocarp forest (Sukri *et al*., 2012).

There were no exotic species recorded in any of the plots studied. Exotic species that have been found in Brunei's forests include *Acacia cincinnata*, *A. mangium* Willd., *A. auriculiformis* A. Cunn. ex Benth., and *A. cincinnata* F. Muell. (Osunkoya *et al*., 2005; Jaafar *et al*., 2022b). Road construction is a known catalyst for invasion by exotic, non-native species (Forman *et al*., 1998; Seiler, 2001; Waddell *et al*., 2020a; 2020b) and the absence of non-native species in the plots may indicate that invasion by exotics was not yet a problem. This may be because the road construction was still ongoing during our study and access to the highway was restricted, likely helping to limit dispersal of non-native tree species. However, we have observed seedlings of exotic *Acacia* species at the forest edges close to the road construction site during our study. Invasion by *Acacia* may become a problem in future at this site, as has happened along the Brunei-Muara coastal highway (Osunkoya *et al*., 2005; Tuah *et al*., 2020; Jaafar *et al*., 2022a; 2022b).

Implications for conservation

This study recorded the presence of three critically endangered species (*Gonystylus bancanus*, *Hopea micrantha,* and *Vatica venulosa*), as well as four endangered species, eight vulnerable species, and 19 near threatened species (IUCN, 2024); Appendix A. This highlights the high conservation value of the Andulau Forest Reserve. Mixed dipterocarp forest on relatively infertile yellow sandy soil is likely one of the most biodiverse terrestrial ecosystems (Ashton, 2010), and the Andulau Forest Reserve is one of the extensively known surviving fragments of this ecosystem. Additionally, several high-value species such as *Eurycoma longifolia* which were recorded in the present study are threatened in the wild by overharvesting (Lee, 2004). Clearing forests for road construction may open pathways for further exploitation of high -value species in the wild. Studies have shown that road construction increases incidences of illegal harvesting and poaching in the previously intact forest (Forman *et al*., 1998; Laurance *et al*., 2009; Laurance *et al*., 2014). The presence of tree species that are considered highly valued timber such as *Koompassia malaccensis* (Leguminosae), *Gonystylus bancanus* (Thymelaceae), and tree species from the family Dipterocarpaceae indicates the high commercial value of the reserve itself in terms of timber availability.

Observations of invasive *Acacia* species near the plots at the forest edge in this study may indicate potential problems of *Acacia* invasion in the future that can have detrimental effects on forest composition and are potentially expensive to manage effectively. Invasive Acacias may also displace or reduce native species, in both plants and animals and may even alter the functioning of the ecosystem (Yusoff *et al*., 2019; Hamad-Sheip *et al*., 2021; Jaafar *et al*., 2022b), further affecting the Andulau Forest Reserve. A point of concern is that our study site is located *ca.* 15 km away from an *Acacia mangium* plantation, which can act as a seed source for the spread of exotic Acacias into the Andulau Forest Reserve (Suhaili *et al*., 2015; Jaafar *et al*., 2022a; 2022b).

Accessibility provided by roads often results in further land-use changes, which could potentially happen to the forest stands near Andulau. This will have detrimental effects on the biodiversity of plants and animal species found in the area. Potential land use change in an area may also demand new transportation resources, which can fragment the remaining forest further (Freitas *et al*., 2010; Laurance *et al*., 2014). Forest fragmentation effects at the Andulau Forest Reserve due to the road construction, particularly effects on ecosystem services (Alamgir *et al*., 2019; 2020) and animal populations (Sodhi *et al*., 2010; Clements *et al*., 2014) require further studies.

CONCLUSION

Our study observed notable changes in forest structure and tree communities near the Telisai-Lumut Highway, suggesting potential impacts on the Andulau Forest Reserve. While rapid changes were recorded, particularly in stem diameter, basal area, and crown characteristics, the results from the biodiversity indices measured did not show significant negative impacts within the three years following highway construction. We propose that tree diversity may exhibit greater variations with the age of road construction and recommend future reassessments to evaluate the long-term effects of highway construction on species composition, tree mortality, and growth.

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Appendix A. Species list for trees ≥ 5 cm dbh collected from study site in Andulau Forest Reserve with Red List status from IUCN.

Family	Species
ACHARIACEAE	*Hydnocarpus* sp. 1 *Hydnocarpus* sp. 2 *Hydnocarpus* sp. 3 *Hydnocarpus sumatranus* (Miq.) Koord.
ANACARDIACEAE	*Anacardiaceae* sp. *Buchanania sessifolia* Blume** *Gluta rugulosa* Ding Hou** *Mangifera parvifolia* Boerl. & Koord.-Schum.** *Mangifera griffithii* Hook.f.● *Mangifera khoonmengiana* Kochummen●● *Melanochyla beccariana* Oliv.** *Parishia maingayi* Hook.f.***
ANISOPHYLLEACEAE	*Anisophyllea corneri* Ding Hou** *Anisophyllea ferruginea* Ding Hou● *Anisophylleaceae* sp.1 *Combretocarpus* sp. 1
ANNONACEAE	*Annonaceae* sp. *Huberantha rumphii* (Blume ex Hensch.) Chaowasku** *Mezzettia havilandii* (Boerl.) Ridl. *Monocarpia kalimantanensis* Kessler** *Phaeanthus splendens* Miq.** *Polyalthia* sp. 1 *Polyalthia* sp. 2 *Polyalthia chrysotricha* Ridl.** *Polyalthia dolichopoda* I.M.Turner *Xylopia ferruginea* (Hook.f. & Thomson) Baill.**
APOCYNACEAE	*Alstonia iwahigensis* Elmer** *Apocynaceae* sp. *Dyera costulata* (Miq.) Hook.f.**
AQUIFOLIACEAE	*Ilex cymosa* Blume**
BURSERACEAE	*Canarium* sp. 1 *Canarium littorale* Blume** *Dacryodes* sp. 1 *Dacryodes costata* (A.W.Benn.) H.J.Lam** *Dacryodes expansa* (Ridl.) H.J.Lam● *Dacryodes incurvata* (Engl.) H.J.Lam** *Dacryodes rostrata* (Blume) H.J.Lam** *Dacryodes rugosa* (Blume) H.J.Lam** *Dehaasia* sp. 1 *Santiria apiculata* A.W.Benn.** *Santiria griffithii* (Hook.f.) Engl.** *Santiria laevigata* Blume** *Santiria tomentosa* Blume**
CALOPHYLLACEAE	*Callophyllum* sp. 1 *Calophyllum* sp. 2 *Calophyllum* sp. 3 *Calophyllum depressinervosum* M.R.Hend. & Wyatt-Sm.** *Calophyllum ferrugineum* var. orientale P.F.Stevens** *Kayea oblongifolia* Ridl. *Kayea beccariana* Baill.** *Mesua* sp. 1 *Mesua* sp. 2

* Note: The following indicates different categories for each species:
(no symbol) Not Evaluated. *Data Deficient. **Least Concern. ***Near Threatened. ●Vulnerable. ●●Endangered. ●●●Critically endangered

Appendix A. (continued)

CANNABACEAE	*Gironniera nervosa* Planch.** *Gironniera parvifolia* Planch.** *Gironniera subaequalis* Planch.**
CARDIOPTERIDACEAE	*Gonocaryum minus* Sleumer**
CELASTRACEAE	*Euonymus castaneifolius* Ridl. *Lophopetalum glabrum* Ding Hou**
CLUSIACEAE	*Garcenia* sp. 1 *Garcinia* sp. 2 *Garcinia* sp. 3 *Garcinia gaudichaudii* Planch. & Triana**
COMBRETACEAE	*Terminalia foetidissima* Griff.**
DILLENIACEAE	*Dillenia excelsa* (Jack) Gilg** *Dillenia sumatrana* Miq.**
DIPTEROCARPACEAE	*Anisoptera marginata* Korth.● *Anthoshorea agami* (P.S.Ashton) P.S.Ashton & J.Heck.*** *Dipterocarpus* sp. 1 *Dipterocarpus borneensis* Slooten*** *Dipterocarpus crinitus* Dyer● *Dipterocarpus geniculatus* Vesque●● *Dipterocarpus lowii* Hook.f.*** *Dryobalanops beccarii* Dyer** *Hopea fluvialis* P.S.Ashton*** *Hopea micrantha* Hook.f.●●● *Hopea beccariana* Burck● *Richetia angustifolia* (P.S.Ashton) P.S.Ashton & J.Heck.*** *Richetia laxa* (Slooten) P.S.Ashton & J.Heck.** *Rubroshorea curtisii* (Dyer ex King) P.S.Ashton & J.Heck.** *Rubroshorea quadrinervis* (Slooten) P.S.Ashton & J.Heck.● *Rubroshorea scabrida* (Symington) P.S.Ashton & J.Heck.*** *Rubroshorea beccariana* (Burck) P.S.Ashton & J.Heck.** *Rubroshorea acuta* (P.S.Ashton) P.S.Ashton & J.Heck.** *Rubroshorea andulensis* (P.S.Ashton) P.S.Ashton & J.Heck.● *Rubroshorea bullata* (P.S.Ashton) P.S.Ashton & J.Heck.● *Rubroshorea kunstleri* (King) P.S.Ashton & J.Heck.** *Rubroshorea macroptera* (Dyer) P.S.Ashton & J.Heck.** *Rubroshorea mecistopteryx* (Ridl.) P.S.Ashton & J.Heck.● *Rubroshorea ovalis* (Korth.) P.S.Ashton & J.Heck.** *Rubroshorea parvifolia* (Dyer) P.S.Ashton & J.Heck.** *Rubroshorea platycarpa* (F.Heim) P.S.Ashton & J.Heck.●● *Rubroshorea rubella* (P.S.Ashton) P.S.Ashton & J.Heck.● *Rubroshorea scaberrima* (Burck) P.S.Ashton & J.Heck.*** *Upuna borneensis* Symington● *Vatica nitens* King*** *Vatica venulosa Blume*●●●
EBENACEAE	*Diospyros* sp. 1 *Diospyros* sp. 2 *Diospyros* sp. 3 *Diospyros areolata* King & Gamble** *Diospyros borneensis* Hiern** *Diospyros dictyoneura* Hiern *Diospyros ferruginescens* Bakh. *Diospyros mindanaensis* Merr. *Diospyros ridleyi* Bakh.** *Diospyros rigida* Hiern

Appendix A. (continued)

ELAOCARPACEAE	*Elaeocarpus mastersii* King**
EUPHORBIACEAE	*Blumeodendron borneense* Pax & K.Hoffm.** *Blumeodendron tokbrai* (Blume) Kurz** *Bridelia* sp. 1 *Bridelia* sp. 2 *Euphorbiaceae* sp. *Hancea penangensis* (Müll.Arg.) S.E.C.Sierra, Kulju & Welzen.** *Koilodepas* sp. *Macaranga conifera* (Rchb.f. & Zoll.) Müll.Arg.** *Macaranga caladiifolia* Becc.** *Macaranga praestans* Airy Shaw** *Macaranga winkleri* Pax & K.Hoffm.** *Mallotus* sp. 1 *Mallotus* sp. 2 *Mallotus* sp. 3 *Mallotus griffithianus* (Müll.Arg.) Hook.f. *Mallotus wrayi* King ex Hook.f.** *Neoscortechinia kingii* (Hook.f.) Pax & K.Hoffm.**
FABACEAE	*Archidendron ellipticum* (Blume) I.C.Nielsen** *Dialium platysepalum* Baker** *Fordia splendidissima* (Blume ex Miq.) Buijsen** *Koompassia malaccensis* Maingay** *Parkia singularis* subsp. *borneensis* H.C.Hopkins● *Sindora beccariana* Backer ex de Wit***
FAGACEAE	*Castanopsis* sp. 1 *Lithocarpus andersonii* Soepadmo *Lithocarpus jacobsii* Soepadmo
IRVINGIACEAE	*Allantospermum borneense* Forman *Irvingia malayana* Oliv. ex A.W.Benn. **
IXONANTHACEAE	*Ixonanthes reticulata* Jack**
LAMIACEAE	*Teijsmanniodendron smilacifolium* (H.Pearson) Kosterm.**
LAURACEAE	*Actinodaphne diversifolia* Merr.** *Alseodaphne bancana* Miq.** *Beilschmiedia* sp. 1 *Beilschmiedia maingayi* Hook.f.** *Litsea elliptica* Blume** *Litsea oppositifolia* Gibbs *Nothaphoebe heterophylla* Merr.** *Phoebe* sp. 1 *Phoebe* sp. 2
LECYTHIDACEAE	*Barringtonia sarcostachys* subsp. *dolichophylla* (Merr.) Prance
LOGANIACEAE	*Norrisia major* Soler.**
MAGNOLIACEAE	*Magnolia liliifera* (L.) Baill.**
MALVACEAE	*Durio* sp. 1 *Durio* sp. 2 *Boschia griffithii* Mast.** *Durio lanceolatus* Mast.*** *Heritiera* sp. 1 *Heritiera aurea* Kosterm.● *Heritiera sumatrana* (Miq.) Kosterm.**

Appendix A. (continued)

MALVACEAE	*Microcos* sp. 1 *Microcos* sp. 2 *Microcos cinnamomifolia* Burret** *Microcos hirsuta* (Korth.) Burret** *Microcos ossea* Burret** *Pentace laxiflora* Merr.** *Scaphium parviflorum* P.Wilkie *Scaphium* sp. 1 *Scaphium* sp. 2 *Scaphium* sp. 3 *Scaphium longipetiolatum* (Kosterm.) Kosterm. *Scaphium macropodum* (Miq.) Beumée ex K.Heyne** *Schoutenia accrescens* (Mast.) Merr.** *Sterculia* sp. 1
MELASTOMACEAE	*Memecylon lilacinum* Zoll. & Moritzi** *Memecylon paniculatum* Jack**
MELIACEAE	*Aglaia foveolata* Pannell*** *Aglaia tomentosa* Teijsm. & Binn.** *Dysoxylum rugulosum* King** *Lansium domesticum* Corrêa
MORACEAE	*Artocarpus odoratissimus* Blanco*** *Artocarpus integer* (Thunb.) Merr.** *Artocarpus kemando* Miq.*** *Artocarpus lamellosus* Blanco *Atrocarpus* sp. 1
MYRISTICACEAE	*Gymnacranthera farquhariana* (Wall. ex Hook.f. & Thomson) Warb.** *Gymnacranthera ocellata* R.T.A.Schouten*** *Horsfieldia carnosa* Warb*** *Horsfieldia crassifolia* (Hook.f. & Thomson) Warb.** *Horsfieldia grandis* (Hook.f.) Warb.** *Horsfieldia polyspherula* (Hook.f.) J.Sinclair** *Knema* sp. 1 *Knema* sp. 2 *Knema stenophylla* subsp. *longipedicellata* (J.Sinclair) W.J.de Wilde** *Knema glaucescens* Jack** *Knema latericia* Elmer** *Knema stenophylla* (Warb.) J.Sinclair** *Merisma* sp. 1 *Myristica iners* Blume** *Myristica smythiesii* J.Sinclair**
MYRTACEAE	*Rhodamnia cinerea* Jack** *Syzygium tawahense* (Korth.) Merr. & L.M.Perry** *Syzgium* sp. 1 *Syzygium* sp. 2 *Syzygium* sp. 3 *Syzygium* sp. 4

Appendix A. (continued)

MYRTACEAE	*Syzygium acuminatissimum* (Blume) DC.** *Syzygium castaneum* (Merr.) Merr. & L.M.Perry* *Syzygium caudatum* (Merr.) Airy Shaw** *Syzygium chloranthum* (Duthie) Merr. & L.M.Perry** *Syzygium confertum* (Korth.) Merr. & L.M.Perry *Syzygium velutinum* A.P.Davis●● *Whiteodendron* sp.
OLACACEAE	*Strombosia ceylanica* Gardner** *Strombosia ceylanica* var. *ceylanica***
PERACEAE	*Chaetocarpus castanicarpus* (Roxb.) Thwaites
PHYLLANTHACEAE	*Antidesma cuspidatum* Müll.Arg.** *Aporosa bullatissima* Airy Shaw *Baccaurea racemosa* (Reinw.) Müll.Arg.** *Baccaurea bracteata* Müll.Arg.** *Baccaurea pubera* (Miq.) Müll.Arg.** *Cleistanthus pyrrhocarpus* Airy Shaw**
POLYGALACEAE	*Xanthophyllum* sp. 1 *Xanthophyllum flavescens* Roxb. *Xanthophyllum ellipticum* Korth. ex Miq.** *Xanthophyllum obscurum* A.W.Benn.**
PRIMULACEAE	*Ardisia* sp.1
RHIZOPHORACEAE	*Carallia brachiata* (Lour.) Merr.**
ROSACEAE	*Prunus* sp. 1
RUBIACEAE	*Dibridsonia conferta* (Korth.) K.M.Wong** *Gaertnera junghuhniana* Miq.** *Gaertnera* sp.1 *Ridsdalea grandis* (Korth.) J.T.Pereira**
RUTACEAE	*Euodia* sp. 1 *Tetractomia tetrandra* (Roxb.) Merr.**
SABIACEAE	*Meliosma sumatrana* (Jack) Walp.**
SAPINDACEAE	*Nephelium cuspidatum* Blume** *Nephelium lappaceum* L.** *Nephelium ramboutan-ake* (Labill.) Leenh.** *Nephelium subfalcatum* Radlk.**
SAPOTACEAE	*Ganua* sp. 1 *Ganua* sp. 2 *Madhuca motleyana* (de Vriese) J.F.Macbr.*** *Madhuca borneensis* P.Royen*** *Madhuca* sp. 1 *Madhuca* sp. 2 *Palaquium cochleariifolium* P.Royen**
SIMAROUBACEAE	*Eurycoma longifolia* Jack**
STEMONURACEAE	*Stemonurus umbellatus* Becc.**
THYMELAEACEAE	*Amyxa pluricornis* (Radlk.) Domke** *Gonystylus bancanus* (Miq.) Kurz●●● *Gonystylus stenosepalus* Airy Shaw***