Article

The Potential of Native Tree Species for Post-Nickel Mining Land Restoration

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Abstract. Due to the absence of topsoil, low pH, and contamination by various heavy metals, revegetation of post-nickel mining land, which is generally carried out by planting economically valuable species, is usually unsuccessful. This study aims to identify tree species suitable for revegetation on post-nickel mining land in Kolaka Regency, Indonesia. Nine plots measuring 20 m x 20 m were distributed in the revegetated post-nickel mining land at three different age categories (1, 5, and 10 years) to observe the growth of revegetation trees, which are introduced species and native tree species that naturally invade the revegetation area. In total, there were 24 tree species found in the revegetated post-nickel mining land consisting of 9 introduced revegetation species and the other 15 tree species were native tree species that invaded the revegetated area. The older the age of the revegetation, the more native plant species are found. In line with the increasing age of revegetation, the density of revegetation plants decreases while the density of native plants increases. The population structure of revegetation trees does not indicate that the species can regenerate, while the inverted shape of the population structure of native plants indicates excellent regeneration potential. Thus, the results of this study recommend making native species, including *Buchanania arborescens*, *Alstonia macrophylla*, *Ficus* sp. *Syzygium* sp. *Colona scabra*, *Litsea* sp., and *Metrosideros* cf. *petiolata* as revegetation plants in former nickel mining areas.

Keywords: revegetation species, native species, regeneration potential, invasion

INTRODUCTION

Open-pit mining is a mining method that extracts minerals from the earth by stripping the surface of the soil. In Indonesia, all the mining companies apply this method for mining nickel. As a result, this mining method creates various environmental impacts on forest and forest soil, including deforestation, loss of fertile soil layers, soil compaction, erosion and sedimentation, landslides, and decreased soil productivity (Monjezi et al., 2009; Zhu et al., 2020). To restore the function of ex-mining land from this mining method, land reclamation and revegetation activities are needed (Pratiwi et al., 2021; Yuan, 2023; Li et al., 2024). The process of revegetation of ex-mining land consists of several stages of activities: (1) species selection, (2) seed procurement, (3) land preparation, (4) soil improvement, (5) determination of planting techniques, (6) maintenance, and (7) monitoring program (Navarro-Ramos et al., 2022; Soendjoto et al., 2023). The revegetation process on post- nickel mining land usually begins with planting ground cover plants to quickly control erosion, then continues with planting trees. During this process, selecting tree species for revegetation is generally the most important step (Massante et al., 2023), considering that not all tree species may be able to adapt to the extreme physical and chemical soil conditions due to the mining activities.

The soil properties in the area after open-pit nickel mining, which is located on the ultramafic rock formation, are very poor, characterized by low N, TC, available P, cation exchange capacity (CEC), exchangeable Ca, and Na (Prematuri et al. 2020). Post-open nickel mining soil is also slow in permeability, cation exchange capacity (CEC), base saturation, and also low P2O5 (Bray) content, acid soil reaction, and organic C, but high exchangeable Fe. (Neswati et al., 2020). In addition, mining activities can release toxic metals into the soil environment (Vischetti et al., 2022; Podgórska & Jóźwiak, 2024). This is because nickel mining is mostly included in the serpentinite geological area which is characterized by the presence of large amounts of trace metal contamination, such as Cr, Ni, and related metals (Mg, Pb, Co, Zn, etc.) with other elements (Chiarucci & Baker, 2007; Kumar & Maiti, 2013).

Nutrient retention, nutrient availability, soil depth, slope, and water availability caused post-nickel mining land to fall into the marginal suitability category for non-timber producing plants (Neswati et al. 2020). Considering the low soil fertility on post-nickel mining land, Pratiwi et al. (2021) suggests selecting fast-growing tree species for revegetating in post-open-pit nickel mining areas (Ahirwal et al., 2020). So far, in fulfilling their obligation to revegetate post-nickel mining land, mining companies in Indonesia have planted non-native, fast-growing species (Prematuri et al., 2020; Purnomo et al., 2022).

Although non native fast-growing tree species are usually early successional species, reforestation in post-nickel mining lands using these species has mostly shown unsatisfactory results (Prematuri et al. 2020). During the care period after planted, these species of tree usually show a fair good growth. This is because various special treatments are given before and after planting the tree seedling, such as preparing a fairly large planting hole filled with topsoil and organic fertilizer, liming around the planting hole to neutralize the soil pH, and also regular fertilizing (Leomo et al., 2021; Jayadi et al., 2022). Therefore, during the care period, the planted non native fast-growing trees generally appear to have relatively good growth. After the maintenance period is completed (usually 5 years), the growth of revegetation trees generally worsens, and many even die. This is because the plant roots have started to spread outside the planting hole and are unable to adapt to the surrounding soil conditions which have lost their fertile layer and are contaminated with toxic metals (Podgórska & Jóźwiak, 2024). It is very common for ex-mining areas that have been revegetated and not maintained for decades to develop into mixed secondary forests dominated by local plant species that are not actually the species planted as revegetation trees. This local tree species is a native pioneer species that invades revegetation areas through natural dispersal mechanisms by various dispersal agents (wind or wildlife) into reclamation areas (Indrajaya et al., 2022).

The failure to grow non-native species should be a lesson that we need to think about ecology when restoring post-mining land, especially post-nickel mining land. Ecologically, post-mining land can recover through natural succession processes (see Vorobeichik, 2022; Morais et al., 2023; Sing et al., 2023), but this may take a long time. Post-mining land restoration is intended to accelerate post-mining land closure and the succession process so that erosion can be controlled and soil fertility restored through litter production and vegetation's absorption of toxins (Li et al., 2024). Once the land conditions are restored, more economically valuable species can be grown.

Recognizing this fact, several studies are currently being conducted to determine the species of native pioneer trees and their growth in post-mining lands. However, almost all publications on post-mining land vegetation restoration using local species are reported from post-coal mining areas (Adman et al., 2020; Haspari et al., 2020). Depending on what type of mineral being mined and the local species are chosen, success stories of planting native tree species in post-mining lands can vary from place to place. For example, Lestari et al. (2019), who conducted observations in post-coal mining lands, found that native species planted could grow and adapt well in reclamation areas despite their slow growth. Research on the diversity of native plant species that can be planted on post-nickel mining land has not been conducted, while nickel mining in Indonesia is currently being carried out massively by clearing forest areas. This study aims to inventory native species that have the potential to be planted as revegetation species in post-nickel mining lands by evaluating native tree species that invade revegetation areas using introduced species at PT. Aneka Tambang (Persero) Tbk. located at Southeast Sulawesi, Indonesia.

MATERIAL AND METHODS

Study Site

This research was carried out from January to February 2013, in the nickel mining concession area of PT Aneka Tambang (Persero) Tbk. in Pomalaa District, Kolaka Regency, Southeast Sulawesi Province (4o10'00" to 4o47'25" SL and 121o31'30" to 121o39'03" EL). The research site has a hilly topography dominated by yellowish-red laterite soil. Nickel ore deposits found in the Pomalaa area include laterite nickel ore which is formed due to the weathering of ultramafic rocks. Based on the climate type classification according to Schmid and Ferguson, the climate at the research location is type A, a wet tropical climate with ultrabasic wet forest vegetation.

Research Plot

Research was conducted in three age categories of post-mining plantation lands: 1 year, 5 years, and 10 years. To ensure that the physical and biological conditions of the study area are well represented, the research plots were purposively distributed about the center of the plantation area. In each age category, we set 3 rectangular plots measuring 20 m x 20 m (400 m²). Each plot was divided into 4 subplots of 10 m x 10 m (100 m²). Tree species planted in 1-year-old plantation areas are *Enterolobium cyclocarpum*, *Gliricidia sepium*, *Gmelina arborea*, and *Vitex coffasus*. In the 5-year-old plantation area, the species of trees planted are *Enterolobium cyclocarpum*, *Acacia auriculiformis*, *Acasia mangium*, *Adenanthera microsperma*, and *Casia seamea*. Meanwhile, in the 10-year-old plantation area, the species of trees planted are *Acacia auriculiformis* and *Acacia mangium*. All planted tree species are introduced (non-native) species.

Measuring Tree Parameter

Every individual tree with more than 130 cm height found in each plot was identified and recorded its species name, measured its diameter or girth at a height of 130 cm above ground. Measurements start from subplot 1 sequentially to subplot 4. If the tree has buttresses more than 130 cm above the ground, the diameter measurement is carried out at 30 cm above the buttress. For calculating the basal area cover, the diameter of trees that branch below a height of 130 cm was measured for each trunk at a height 130 cm above grown (or 30 cm above the branches when the branches located close to the height of 130 cm), but it is counted as a single individual.

Saplings with a height of 130 cm or less were identified, and their height was measured on a 10 m x 10 m subplot that was made and placed systematically on each subplot. To avoid double measurement, each tree is marked with yellow paint after measurement. Herbarium specimens were taken from trees that were not identified in the field. Species identification was made in the Herbarium section of the Laboratory of Forest Resources Conservation and Ecotourism, Hasanuddin University in Makassar.

Data Analyses

Raw data from the field was used to calculate the dominance (basal area) of each species using. The invasion ability of native species into the planted area was analysed by comparing the density, basal area, and frequency between revegetation species and native species that invaded revegetated areas at each age category. The population structure between planted species and invaded species was presented in the form of a bar diagram by grouping each species into four life stages: seedling (individuals lower than 130 cm in height); sapling (individuals taller than 130 cm in height but smaller than 10 cm in diameter); pole (individuals with diameter between 10 – 20 cm); and tree (individual with diameter more than 20 cm). The regeneration abilities of the planted species and the species that invade the revegetation areas are analyzed by comparing their population structures.

RESULTS

Species Found in the Plot of 1 Year Revegetation

Six species consisting of four deliberately planted for revegetation purposes (hereinafter referred to as "revegetation species") and two local species that naturally invaded the revegetation area (hereinafter referred to as "native species") were found in the three plots of 1-year revegetation area (Table 1). The four species planted as revegetation species are all introduced species. Two revegetation species, *Enterolobium cyclocarpum* and *Gliricidia sepium* had grown to a height of >130 cm a year after being planted. No *Gmelina arborea* and *Vitex coffasus* reached a height of more than 130 cm a year after being planted. The two native species consisted of *Alstonia macrophylla* and *Buchanania arborescens*.

Table 1. Density, frequency, and maximum diameter of trees >130 cm in height in the area 1 year after revegetation

No.	Species	Density (Tree/400 m²)			Mean Density (Tree/400 m²)	F (%)	D$_{Max.}$ (cm)
		P1	P2	P3			
	Individuals >130 cm in height						
1.	*Enterolobium cyclocarpum**	20	21	17	19.33	100	5.41
2.	*Gliricidia sepium**	12	9	9	10.00	100	3.18
	Total Density per Plot	32	30	26	29.33		
	Individuals <130 cm in height						
1.	*Gmelina arborea**	16			5.33	33	
2.	*Vitex coffasus**			16	5.33	33	
3.	*Alstonia macrophylla*		16		5.33	33	
4.	*Buchanania arborescens*			16	5.33	33	
	Total Density per Plot	16	16	32	21.33		

*: Revegetation species

In line with their density, the total basal area of *Enterolobium cyclocarpum* was much larger (almost twice) than that of *Gliricidia sepium* (Table 2). Even though it was planted deliberately, *Gliricidia sepium* was not the main tree species for revegetation but a species of shrub that was planted among the main tree species to speed up the land-covering process. This species is often planted on marginal land because it is known for being able to fix nitrogen from the air. The maximum diameter was 5.41 cm shown by *Enterolobium cyclocarpum*.

Table 2. The basal area of trees with a height >130 cm in the area 1 year after revegetation

No.	Species	BA (cm²/400 m²)			Mean BA (cm²/400 m²)
		P1	P2	P3	
1.	*Enterolobium cyclocarpum**	370.93	408.75	329.85	369.84
2.	*Gliricidia sepium**	72.48	52.78	60.70	61.99
	Total Basal Area	443.73	461.53	390.55	431.83

Species Found in the Plot of 5 Years Revegetation

In three plots set in the 5-year revegetation area, a total of nine species were found – six of which had reached a height of >130 cm, and three other species had not yet reached a height of 130 cm (Table 3). The six individuals that have reached a height >130 cm consisted of five revegetation species and one native species. Meanwhile, the five species that had not yet reached a height of 130 cm consisted of four native species and one revegetation species. Some individuals of *Cassia siamea*, which was a revegetation species, had not reached more than 130 cm in height within 5 years after being planted. *Buchanania arborescens* was a native species that reaches more than 130 cm in height. *Melastoma malabatricum* was a native species of shrub. Just like in the 1-year revegetation area, the main species planted in the 5-year revegetation area was also *Enterolobium cyclocarpum*.

Table 3. Density, frequency, and maximum diameter of trees >130 cm in height in the area 5 years after revegetation

No.	Species	Density (Tree/400 m²)			Mean Density (Tree/400 m²)	F (%)	$D_{Max.}$ (cm)
		P1	P2	P3			
	Individuals >130 cm in height						
1.	*Enterolobium cyclocarpum**	18	18	13	16.33	100	5.4
2.	*Buchanania arborescens*	14	13	16	14.33	100	7.9
3.	*Acacia auriculiformis**		2		0.66	33	3.8
4.	*Acacia mangium**			1	0.33	33	9.5
5.	*Adenanthera microsperma**			1	0.33	33	1.9
6.	*Cassia seamea**			1	0.33	33	2.8
	Total Density per Plot	32	33	32	32.33		
	Individuals <130 cm in height						
1.	*Buchanania arborescens*	32	48	16	32	100	
2.	*Alstonia macrophylla*	16	-	16	10.66	67	
3.	*Cassia siamea**	32	-	-	10.66	33	
4.	*Morinda* cf. *elliptica*	-	16	-	5.33	33	
5.	*Melastoma malabatricum*	-	16	-	5.33	33	
	Total Density per Plot	80	80	32	64.00		

*: Revegetation Species

The mean density per plot of the revegetation species that have reached a height of >130 cm was 17.98, ranging from 0.33 to 16.33 individuals per plot (Table 3). The density of *Adenanthera microsperma*, and *Cassia siamea* was low and did not appear to grow successfully. *Acacia auriculiformis* and *Acacia mangium* were complementary revegetation species, therefore, these species were not found in all plots. One of the local species that naturally invade the area, *Buchanania arborescens*, shows high density both for the individuals that have reached >130 cm of height and those that have not yet reached 130 cm of height. This species spread naturally and evenly on all three plots set on the area of 5 years after revegetation. The maximum diameter was 9.5 cm shown by a revegetation species *Acacia mangium*, the second maximum diameter was 7,9 cm shown by *Buchanania arborescens*, whilst the third maximum diameter was 5.4 shown by *Enterolobium cyclocarpum*. Although its diameter is only the third maximum, the basal of *Enterolobium cyclocarpum* was the largest (Table 4). This may be caused by its highest density per plot, and in addition as the planted species, the range between the value of maximum and minimum diameter did not vary widely.

Table 4. The basal area of trees with a height >130 cm in the area 5 years after revegetation

No.	Species	BA (cm²/400 m²)			Mean BA (cm²/400 m²)
		P1	P2	P3	
1.	*Enterolobium cyclocarpum**	1,469.82	1,512.65	1,556.65	1,513.10
2.	*Buchanania orborescens*	331.76	310.74	480.57	374.36
3.	*Acacia auriculiformis**		19.42		6.47
4.	*Acacia mangium**			71.65	23.88
5.	*Adenanthera microsperma**			1.91	0.63
6.	*Cassia seamea**			13.53	4.51
	Total Basal Area	1,801.58	1,842.81	2,124.31	1,922.95

*: Revegetation Species

Species Found in the Plot of 10 Years Revegetation

In the three plots set in the area 10 years after revegetation, 14 tree species were found (Table 5). The 14 tree species consisted of two revegetation species: *Acacia auriculiformis* and *Acacia mangium*. The other 12 species, which were found in all three plots, were native species that invade the revegetation areas. All

revegetation species had reached a height of >130 cm, but one of the native species - Rubiaceae 2 - had not yet reached a height of >130 cm.

Table 5. Density, frequency, and maximum diameter of trees >130 cm in height in the area 10 years after revegetation

No.	Species	Density (Tree/400 m^2)			Mean Density (Tree/400 m^2)	F (%)	D$_{Max}$ (cm)
		P1	P2	P3			
	Individuals >130 cm in height						
1.	*Acacia auriculiformis**	23	17	15	18.33	100	16.59
2.	*Acacia mangium**	5	2	2	3.00	100	23.24
3.	*Buchanania arborescencs*	5	18	13	12.00	100	10.50
4.	*Alstonia macrophylla*	12	3	2	5.66	100	2.54
5.	*Sarchoteca diversifolia*	-	4	5	3.00	67	4.77
6.	*Morinda* cf. *elliptica*	-	-	1	0.33	33	1.91
7.	*Calicarpa* sp.	1	-	-	0.66	67	1.91
8.	*Colona scabra*	1	-	1	0.66	67	1.91
9.	*Ficus* sp.	1	-	-	0.33	33	1.91
10.	*Syzygium* sp.	1	-	-	0.33	33	1.91
11.	Rubiaceae 1	-	1	-	0.33	33	0.63
12.	*Litsea* sp	-	1	-		33	1.59
13.	*Metrosideros* cf. *petiolata*	-	-	1		33	1.91
	Density per Plot	49	46	40	45.00		
	Individuals <130 cm in height						
1.	*Buchanania arborescens*	48	32	64		100	
2.	*Alstonia macrophylla*	16	16	-	10.66	67	
3.	*Sarchoteca diversifolia*	16	16	16	10.66	100	
4.	Rubiaceae 2	-	16	-	5.33	33	
	Density per Plot	80	80	80	80.00		

* : Revegetation Species

The two revegetation species and twelve native species had reached a height >130 cm so their diameters could be measured and basal areas could be calculated (Table 6). The mean density per 400 m^2 of trees with a height >130 cm in the area 10 years after revegetation was 45, consisting of 21.33 revegetation tree species per 400 m^2 and 28.67 native tree species per 400 m^2. *Buchanania arborescens* showed the highest density among native species and was found in all three plots. The maximum diameter of 23.24 was represented by *Acacia mangium*. *Buchanania arborescens* showed the largest maximum diameter among native species. In line with its highest density, the basal area of *Acacia auriculiformis* was also the largest. The basal area of *Buchanania arborescens* was the largest among native species but was still smaller compared to that of revegetation species.

Growth Comparison Between Revegetation and Native Species

As the age stage increases, the tree density of revegetation species tends to decrease (Fig. 1 top left), but that of native species increases (Fig. 1 bottom left). Maximum height shows a similar tendency between revegetation species (Fig. 1 top center) and native species (Fig. 1 bottom center), taller in the older age stages. In all age stages, the maximum height of the revegetation tree species was higher than native tree species. Like the maximum height, the maximum diameter of revegetation species (Fig. 1 top right) and native species (Fig. 1 bottom right) also show an increase as the age stage increases. In line with the maximum height, the maximum diameter of the revegetation species was larger than native species.

Table 6. The basal area of trees with a height >130 cm in the area 10 years after revegetation

| No	Species	BA (cm²/400 m²)			Mean BA (cm²/400 m²)
		P1	P2	P3	
1.	*Acacia auriculiformis**	2,002.62	1,568.15	214.33	1,261.70
2.	*Acacia mangium**	858.04	672.92	750.39	760.45
3.	*Buchanania arborescens*	65.36	390.36	310.50	255.41
4.	*Alstonia macrophylla*	29.93	6.44	5.73	14.03
5.	*Sarcotheca diversifolia*	-	46.49	53.02	33.17
6.	*Morinda* cf. *elliptica*	-	-	6.44	2.14
7.	*Calicarpa* sp.	17.91	-	-	5.97
8.	*Colona scabra*	2.86	-	2.86	1.91
9.	*Ficus* sp.	5.09	-	-	1.69
10.	*Sizygium* sp.	2.86		-	0.95
11.	Rubiaceae 1	-	2.86	-	0.95
12.	*Litsea* sp.	-	0.31	-	0.10
13.	*Metrosideros* cf. *petiolata*	-	-	1.99	0.66
	Basal Area Per Plot	2,984.67	2,687.53	1,345.26	2,339.13

* : Revegetation Species
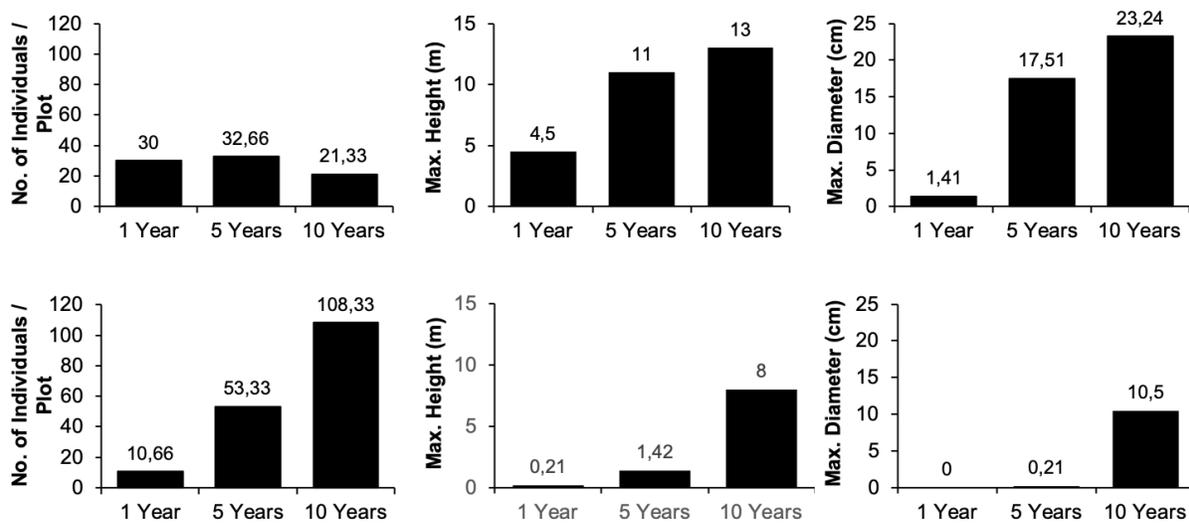
Figure 1. Density (left), maximum height (center), and maximum diameter (right) of revegetation species (top line) and native species (bottom line)

Regeneration Potential of Revegetation and Native Species

As mentioned previously, there were two revegetation species in the 10-year revegetation plot: *Acacia auriculiformis* and *Acacia mangium*. Apart from that, several native species were also found invading revegetation areas, dominated by *Buchanania arborescens*, *Alstonia macrophylla*, and *Sarcotheca diversifolia*. To determine the regeneration potential between revegetated species and native species, we analyzed their population structure (Fig. 2). There were very striking differences in population structure between revegetation species and native species, where the population structure of revegetation species showed a "J" shape while the population structure of invasive species showed an inverted "J" shape. These data indicate that the revegetation species have not started to reproduce even after 10 years of planting.
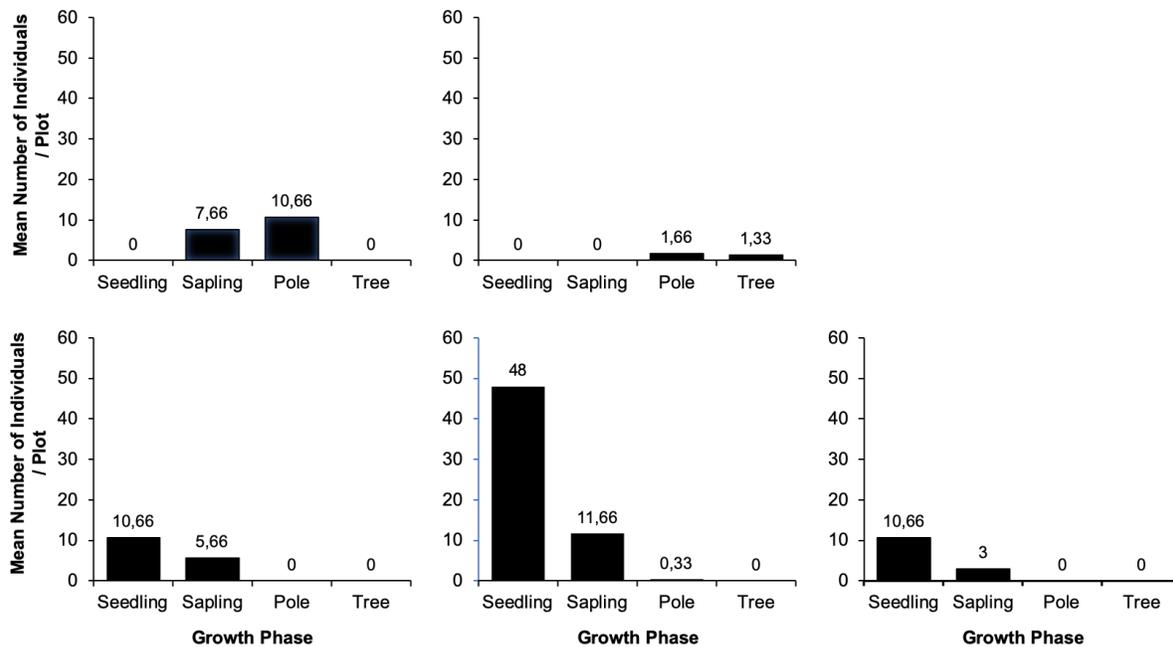
Figure 2. Population structure of *Acacia auriculiformis* (top left), *Acacia mangium* (top right), *Buchanania arborescens* (bottom left), *Alstonia macrophylla* (bottom center), and *Sarcotheca diversifolia* (bottom right)

DISCUSSION

Twenty-four tree species were found in nine plots placed in three age categories (1, 5, and 10 years) after revegetation at PT Antam (Persero) UBP Nikel. Nine of these are revegetation trees, while the other 15 are native trees that naturally invaded the revegetation area. The composition and density of native tree species varied across the age groups of revegetation stands. The older the revegetation, the denser and more diverse species were invading the revegetation area. Some native species present in the old revegetation stage are absent in the new revegetation stage.

Native species that invade revegetation areas can be classified into short-lived pioneer (*Calicarpa* sp., *Morinda* cf. *elliptica*, *Sarchoteca diversifolia*, Rubiaceae 1, and Rubiaceae 2.), and long-lived pioneer species (*Buchanania arborescens*, *Alstonia macrophyla*, *Ficus* sp. *Syzygium* sp. *Colona scabra*, *Litsea* sp. and *Metrosideros* cf. *petiolata*). Short-lived pioneer species are small trees and will die if shaded by taller trees. Long-lived pioneer species are large trees that can survive in dense secondary forests, but their seeds may not germinate and grow beneath the dense canopy of their parent tree (Santos et al., 2012; Tiebel et al., 2018; DeArmond et al., 2022). *Syzygium* is a species commonly found in primary forests (Brambach et al., 2017), where its recalcitrant seeds can germinate and survive under the dense forest canopy.

Regardless of species composition and growth rate, this study showed differences in density dynamics per plot between revegetation species and species that invaded the revegetation area. In the 1-year and 5-year revegetation categories, there was no difference in the density of revegetation trees, but in the 10-year age category, the density of revegetation trees was distinctly lower. Trees planted for revegetation are cared for three to five years after planting (Soendjoto et al., 2023). By the technical instructions issued by the Directorate of Open Access Land Damage Restoration, Directorate General of Environmental Pollution And Damage Control, Ministry of Environment And Forestry of the Republic of Indonesia (2016), revegetation trees are fertilized, weeded, and replanted if any trees die during care. After five years, the revegetation trees are no longer cared for and allowed to grow naturally. The decrease in revegetation tree density at the age of 10 years may be interpreted as some trees begin to die after being no longer cared for. In contrast to the revegetation species, the species diversity as well as the density of native species that invade the revegetation areas are continuously increasing.

The population structure of revegetation tree species shows a J shape, and conversely, the population structure of native tree species shows an inverted J shape. These two different shapes indicate differences

in regeneration ability(Alessandrini et al., 2011; Vlam et al., 2017; Ghanbari et al., 2021). The J shape of the population structure of revegetation tree species indicates that there are few or no young stages of the species. In other words, the species has weak or no regeneration ability in the post-nickel mining land. In contrast to the J shape, the inverted J shape of the population structure of native tree species indicates that there are many saplings available in the post-nickel mining land. Young native trees found in the revegetation area of the post-nickel mining land are likely not yet starting to bear fruit. The abundance of native saplings is likely to have germinated from seeds dispersed by parent trees growing around the revegetation area (see Raffles Museum of Biodiversity Research, 2013 for *Buchanania arborescens* and *Alstonia macrophylla*). Thus this study indicates that native species have a good ability to grow and regenerate naturally in the post-nickel mining land.

Mining activities to explore different types of minerals will certainly have different impacts on the environment (for example, Bian et al., 2010 for coal; Laker, 2023 for gold; Lu et al., 2023 for copper). However, regardless of the type of mineral mined, post-mining land is usually contaminated with various pollutants, especially heavy metals (Podgórska & Jóźwiak, 2024; Wong et al., 2024), and no longer has a topsoil layer (Lei et al., 2016; Hu et al., 2020). Reclamation actions—where revegetation is one of the stages of the process—are essential to restoring the condition of post-mining land (Šofranko et al., 2020; Rahmonov et al., 2022). Due to the lack of understanding of ecological processes, the government and the community generally hope that post-mining land can be planted with agricultural commodities or trees of economic value. At the trial level, several studies have reported success stories of planting agricultural commodities on non-metal post-mining land with various treatments (Howieson et al., 2017; Ansahar et al., 2022). However, until now, no report has stated that post-mining land can be developed to plant agricultural commodities on an economic scale. On the contrary, many studies report how bad post-mining soil conditions are (Nadalia & Pulunggono, 2011; Podgórska & Jóźwiak, 2024), and are not suitable to plant agricultural commodities (Kartawisastra & Gani, 2020).

This study revealed that, in post-nickel mining lands, planting of introduced fast-growing species showed very low success. Meanwhile, native species naturally invading post-mining lands are more diverse, grow better, and show good regeneration potential. This shows that newly reclaimed post-mining land is not ready to support the growth of non-native plant species with economic value, such as timber tree species and agricultural commodities. Therefore, selecting introduced species as revegetation trees based solely on economic value considerations is not an entirely correct decision. In the early stages of post-mining revegetation process, rapid improvement of habitat conditions (especially soil conditions), is essential and should take precedence over economic considerations (Swab et al., 2017; König et al., 2022). Post-mining land conditions must first be restored by planting native or local trees (Kneller et al., 2018; Gairola et al., 2023). These species will grow naturally and thrive in the area without any care. Efforts to plant timber tree species or crops will only be successful after soil conditions improve. Ecologically, tree species that are naturally adapted to grow in areas with different mineral content will also be different. This study shows that in areas with nickel mining materials, the native species of long-lived pioneer trees that can grow well naturally on the post-nickel mining land are *Buchanania arborescens*, *Alstonia macrophylla*, *Ficus* spp. *Syzygium* sp. *Colona scabra*, *Litsea* sp. and *Metrosideros* cf. *petiolata*.

This study may not reveal all native tree species that have the potential to revegetate post-nickel mining areas. During this study, pioneer trees such as *Dillenia serrata* and *Alphitonia incana* were frequently found growing naturally on roadsides in post-nickel mining areas. Some of the species mentioned above only have the genus name followed by the abbreviation "sp" because they do not yet have a specific epithet. If the species is to be used as a revegetation tree, specimens should be taken to guide the search for the correct tree as a seed source.

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AUTHOR CONTRIBUTIONS

Putu Oka Ngakan: Conceptualization, project administration, funding acquisition, supervision, writing original draft, review, and editing. Fadli Suhati: Methodology, supervision, review, and editing. Risma Illa Maulany: review and editing. Nasri Nasri: review, and editing. Andi Siady Hamzah: review and editing. Putu Supadma Putra: review and editing. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors of this paper declare that they have no affiliation or involvement with any organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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