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Vegetation Condition and Potential Seed Rain in a Fire-Affected Tropical Forest Ecosystem Dominated by the Endangered *Eucalyptus urophylla* in Mutis Forest, East Nusa Tenggara-Indonesia

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ABSTRACT

Global deforestation and climate change-induced forest fires disrupt tropical forest functions. On the other hand, fires can be ecologically beneficial by increasing seed rain diversity and regeneration. In the Mutis forest, Indonesia, recurrent fires and deforestation threaten the endangered native species *Eucalyptus urophylla*. This study compared vegetation and seed rain between burned and unburned areas of the Mutis forest. Vegetation data were collected from 50 plots (10×10 m), in each area by measuring trees with a diameter at breast height (DBH; 1.3 m above ground level) ≥3 cm. Seed rain was collected for seven months using 50 seed traps (Ø 50 cm) in each area. The results showed that *Eucalyptus urophylla* has a significant ecological role in the both sites, as shown by its highest Importance Value Index (IVI) in both burned (177.05%) and unburned sites (115.70%). Four seed species were found in both sites, i.e., *E. urophylla*, *Olea paniculata*, *Pittosporum timorense*, and *Rapanea hasseltii*. The most abundant seeds were *E. urophylla*, 435 seeds at the burned site and 314 seed at the unburned site, indicating their origin from local vegetation. Seed species diversity was low in both burned (Shannon H'=0.21) and unburned (H'=0.39) areas. Therefore, conservation are necessary to maintain the sustainability of this forest. Recommended actions included seed collection in April to May, cultivation of *E. urophylla* for post-fire restoration, and implementing fire management strategies in the Mutis forest area.

HIGHLIGHTS

Mutis forest shows apparent vegetation shifts due to fire disturbances. Burned plots are dominated by fire-tolerant *Eucalyptus urophylla*. Most of the seed rain collected originated from plants present in the area. Low seed diversity may hinder natural forest regeneration.

1. INTRODUCTION

Global deforestation is an escalating threat to biodiversity and the ecological integrity of tropical forests, driven primarily by human activities like extensive logging and land-use conversion (Gould et al., 2024). In addition, climate change exacerbates forest degradation through rising temperatures, irregular rainfall patterns, prolonged droughts, and increasingly intense wildfires (IPCC, 2023). There are three common types of fires, namely (1) underground fires that occur in the organic soil layer, (2) surface fires that occur just above the soil surface, and (3) crown fires that occur in the crowns of trees (Bond and van Wilgen, 2013). Wildfires can alter vegetation structure and composition, inhibit natural regeneration, and reduce the abundance and diversity

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of plant species (Arasa-Gisbert et al., 2024; Chalermsri et al., 2020). Fires can significantly alter ecosystem processes across a landscape, including increasing soil erosion (Bond and Keane, 2017), changing forest composition, and directly impacting vegetation, which may lead to long-term changes in forest structure and ecosystem function (Armenteras et al., 2021).

Nevertheless, fires can also provide ecological benefits, such as increasing seed rain diversity in disturbed areas compared to undisturbed ones (Leder et al., 2022). Regularly occurring fires can eradicate invasive species and promote the growth of native plants. In addition, fire-adapted plants, such as certain grasses and shrubs, often emerge after a fire, creating opportunities for local wildlife to return and thrive (Pivello et al., 2021). Fire can also trigger flowering, seed dispersal, or seed germination (Bond and Keane, 2017) and seed development in Eucalyptus (Florence, 2004). Seeds from plant families including Anacardiaceae, Apiaceae, Cistaceae, Convolvulaceae, Fabaceae, Malvaceae, and Rhamnaceae are known to germinate when exposed to heat from fires (Keeley and Pausas, 2022).

Repeated deforestation and wildfires contribute to a decline in mature tree populations, disrupting natural seed rain potential (Arasa-Gisbert et al., 2024). Seed rain constitutes a crucial ecological process and serves as a key indicator of vegetation regeneration, reflecting the spatial distribution and abundance of seeds dispersed by abiotic and biotic agents, including wind, gravity, and animals (Baskin and Baskin, 2014; Rocha et al., 2021). It plays an essential role in facilitating natural regeneration, shaping initial species composition, and influencing successional pathways (Huanca Nuñez et al., 2021). Vegetation influences seed rain dynamics through various mechanisms (Rocha et al., 2021), and seed rain analysis offers valuable insights into ecosystem conditions (Procknow et al., 2020).

Indonesia ranks third in the world in terms of deforestation rates over the past decade (FAO, 2020). One of the most affected by deforestation and recurring forest fires is the Mutis forest, located in the East Nusa Tenggara Region. Fires in the Mutis Timau area are dominated by surface fires (Kaho and Marimpan, 2014). The dominant vegetation in this area is *Eucalyptus urophylla*, a species native to Indonesia and Timor-Leste (IUCN, 2019; Monk et al., 2000), which is naturally distributed throughout much of eastern Indonesia (Pepe et al., 2004). Despite its important ecological role in maintaining the structure and function of local ecosystems, this species has been categorized as Critically Endangered on the IUCN Red List, with a projected population decline exceeding 50% over the next century (IUCN, 2019).

Eucalyptus urophylla is a resilient species that grows rapidly in soils with limited organic matter content (Monk et al., 2000), making it commercially significant (Barros et al., 2022). It typically initiates flowering during the dry season, with seed maturation occurring within approximately six months. The species relies predominantly on biotic pollinators—such as insects, birds, and mammals—while wind contributes only marginally to the pollination process (Sein and Mitlöhner, 2011). Even though genus Eucalyptus was known to have limited distribution capacity (Booth, 2017), its epicormic resprouting structure facilitates regeneration after disturbance (Crisp et al., 2011), resulting in the resilience of *E. urophylla* to persist. Fire acts as an ecological driver influencing the spatial regeneration of Eucalyptus (Dorrough and Moxham, 2005). For example, seedlings of *Eucalyptus regnans* have been observed to regenerate vigorously after moderate to high-intensity fires in southeastern Australia, particularly in areas with adequate rainfall (Smith et al., 2016).

The potential of fire to affect vegetation dynamics, including seed rain production, and forest regeneration in a forest dominated by Eucalyptus, has been widely studied. However, no studies have yet been done in a forest dominated by *E. urophylla*, such as Mutis forest. Therefore, this study aimed to compare vegetation, forest structure, and seed rain conditions in burned and unburned areas within Mutis forest. The outcome of this study is expected to provide foundational insights into seed rain dynamics and also serve as basic information for conservation and restoration efforts in the Mutis Timau National Park Area.

2. METHODOLOGY

2.1 Study area

This study was conducted at the Mutis forest area, a part of Mutis Timau National Park, East Nusa Tenggara, Indonesia. Before being declared a national park, Mutis forest was a nature reserve covering an area of 12,315.61 ha. The status was officially changed on 8 September 2024, to Mutis Timau National Park following the issuance of Decree of the Minister of Environment and Forestry No. 946 of 2024. The national park covers a total area of 78,789 ha, including Mutis forest and Mutis Timau Protection forest (Rahmat, 2024). Mutis forest receives the highest rainfall on Timor Island, with an annual average of 2,000-3,000 mm. The rainy season last from November to March, and temperatures ranging between 14°C to 29°C in normal conditions and reaching 9°C in extreme conditions (BBKSDA NTT, 2018; Putri et al., 2024). Fires in the Mutis forest area usually occur between August and October (Kaho and Marimpan, 2014).

Data collection was done from February to September 2023 in forested areas within the administrative boundaries of Fatumnasi Village. According to data from the Mutis Nature Reserve Resort Centre (unpublished), this region experienced a high incidence of forest fires in 2019. The research period was selected with consideration for environmental factors including weather conditions and rainfall. The study sites (Figure 1) were classified into burned areas and unburned areas based on the presence or absence of visible fire scars on the trunks of *Eucalyptus urophylla* trees, which served as indicators for site classification. A general description of the study site is presented in Table 1.

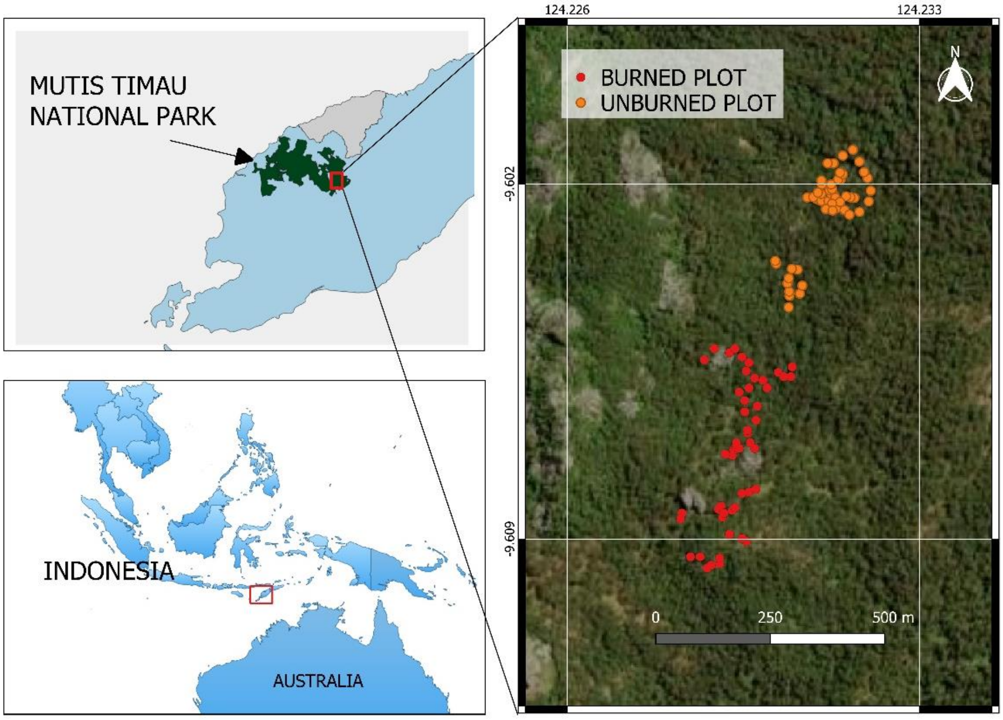

Figure 1. The location of study sites in Mutis Forest, East Nusa Tenggara, Indonesia

Table 1. General description of the study location

Description	Mutis Timau National Park Study Location	
	Burned area	Unburned area
Village	Fatumnasi	
Geologic conditions[a]	A mixture of volcanic rock and limestone[a]	
Annual rainfall (mm)[b]	2,000-3,000[b]	
Temperature conditions [b] (°C)	14-29[b]	
Longitude	124°13'41"- 124°13'49" E	124°13'46"- 124°13'53.6" E
Latitude	9°36'32.4" -9°36'21.6" S	9°36'06" -9°36'26.2" S
Soil conditions[c]		
- Average organic C (%)	9.16[c]	7.19[c]
- Average pH of soil	4.6[c]	3.9[c]
- Soil Humidity (%)	71.7[c]	81.3[c]

[a] (Fisher,L et al., 1999); [b] (Putri et al., 2024); [c] (Research documentation, analyzed in laboratory, unpublished data)

2.2 Vegetation survey

Due to limited accessibility and existing field conditions in the forest area, the site selection was influenced by resource limitations and environmental factors, including extreme weather and landslides that occurred during the data collection period. The lack of replication at the treatment level is a limitation of this study. Vegetation measurements were conducted in February to March 2023 using 10×10 m plots. A total of 50 plots were established in each area. Plots were randomly placed approximately 30 m from the trail to minimize edge effects. In each plot, all trees with a diameter at breast height (DBH, measured at 1.3 m above ground level) of at least 3 cm were measured, marked, and identified.

Soil pH and moisture were measured directly in the field. Soil samples were collected for analysis of organic carbon content at the Kupang State Polytechnic laboratory. Rainfall data during the study period were obtained from unpublished records provided by the Ministry of Public Works and Housing of Indonesia. Plant samples were collected and identification was done at Herbarium Bandungense, Institute of Technology Bandung, with assistance from a curator and a plant identification application (Yang et al., 2022).

2.3 Seed rain collection

Seed rain of tree species was collected by installing seed traps in the study area dominated by *E. urophylla*. The vegetation plots were located around the seed traps. Since the seeds of *E. urophylla* and several other species were relatively small, the seeds that were collected and analysed were the ones that were still in the capsule. Fifty traps on each site were installed in February 2023. Traps used were a conical or funnel-shaped seed trap made of mesh with a surface area of 0.196 m² each (Figure 2), resulting in a total seed capture area of 9.8 m². Each trap was tied to 3 poles at a height of 1 m above the ground. Seed traps were set randomly, and purposive sampling was performed with a minimum distance of 10 m between traps.

Seeds were collected from the traps from March to September 2023. The sampling process encountered significant challenges due to extreme weather, landslides, and the substantial loss of traps. Initially, seed collection was planned every 10 days. However, due to limited human resources in the field and unpredictable weather conditions, the seed collection intervals were not the same. Nonetheless, up to two seed collections were conducted in each month, resulted in a total of twelve collections. During the collection, some seed traps were unusable due damage caused by strong winds, heavy rainfall, and being stolen. These disruptions occurred sporadically during the collection period. More details on the seed collection period and the condition of seed traps are presented in Table 2.

Figure 2. The setup of the seed trap at the study site

The number of seed traps decreased significantly since the first data collection (S01). At the end of data collection (S12), only 14 seed traps remained, consisting of six seed traps in burned area and eight seed traps in unburned area. Even though the traps were set in areas that human rarely visited, the decrease in the number of functioning traps was mainly due to human activities, especially individuals entering the forest to collect wood. Subsequently, the data for seed rain presented in this study utilized data obtained from traps that could record data consistently from the first to the 12th data collection. There were 12 collections periods in total, with a minimum interval of 11 days between collections. The collected seeds were classified into three categories, i.e., category I: damaged or rotten fruits or seeds; category II: fruits or seeds that were intact, ripe, and had no damage or decay; category III: fruits or seeds that were young, small, and immature but not damaged or rotten.

Table 2. The seed collection period and the number of remaining seed traps

Sampling codes	Period	Burned area		Unburned area	
		Time range of seed collection	Number of remaining traps	Time range of seed collection	Number of remaining traps
S01	February	20 February - 8 March 2023	49	15 February-4 March 2023	50
S02	March - I	9 March-20 March 2023	45	5 March- 21 March 2023	50
S03	March - II	21 March - 3 April 2023	42	22 March- 3 April 2023	48
S04	April - I	4 April - 14 April 2023	38	4 April - 14 April 2023	48
S05	April - II	15 April - 5 May 2023	31	15 April-5 May 2023	43
S06	May - I	6 May - 19 May 2023	29	6 May-19 May 2023	41
S07	May - II	20 May - 2 June 2023	17	20 May-2 June 2023	33
S08	June	3 June - 26 June 2023	15	3 June-26 June 2023	33
S09	July - I	27 June-14 July 2023	13	27 June-14 July 2023	30
S10	July - II	15 July-5 August 2023	12	15 July-5 August 2023	28
S11	August	6 August -30 August 2023	11	6 August -31 August 2023	21
S12	September	31 August -21 September 2023	**6**	1 September-21 September 2023	**8**

2.4 Data analysis

- Vegetation structure and seed rain condition

The data analysis was done using Minitab® 21.4.3 (64-bit). The species density (Di) at the plot level was calculated using Equation (1) (Tebabal et al., 2024):

$$\text{Species Density (individual/ha)} = \frac{\text{The number of a species (individual)}}{\text{Total area sampled (ha)}} \quad (1)$$

The Mann-Whitney test was used to compare vegetation at burned and unburned locations.

The differences in forest structure, species composition, and forest similarity were measured using the Important Value Index (IVI), which was calculated as Equation (2):

$$\text{Important Value Index (IVI\%)} = (\text{RDi}) + (\text{RFi}) + (\text{RDo}) \quad (2)$$

Where; RDi is Relative density, RFi is Relative frequency, RDo is Relative dominance, which were calculated using Equation (3), (4), (5):

$$\text{Relative Density (RDi \%)} = \frac{\text{Density of a species}}{\text{Density of all species}} \times 100\% \quad (3)$$

$$\text{Relative Frequency (RFi \%)} = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \times 100\% \quad (4)$$

$$\text{Relative Dominance (RDo \%)} = \frac{\text{Dominance of a species}}{\text{Dominance of all species}} \times 100\% \quad (5)$$

The species diversity of an area and colected seeds were analyzed the Shannon-Wiener index for both burned and unburned area (Shannon and Weaver, 1949).

The Chi-square test was used for the analysis of differences in the distribution of DBH classes of *E. urophylla* and other species in burned and unburned sites.

The Kruskal Wallis test was used to analyse differences between seed categories (CI, CII, CIII) in burned and unburned locations.

The relationship between stand density and seed density in burned and unburned sites was analysed using Spearman correlation. This correlation was also used to analyse the relationship between rainfall and seed density.

3. RESULTS

3.1 Condition and structure vegetation in fire-affected and intact forest sites

Vegetation surveys of trees with DBH ≥3 cm revealed that the burned area has slightly less diverse trees (10 families, 12 species) with a lower density (702 individuals/ha) than the unburned area (11 families, 14 species, 790 individuals/ha. However, Mann-Whitney U test showed no significant difference between the sites ($p=0.201$; $p>0.05$). The burned area was dominated by *E. urophylla*, with a density of 364 individuals/ha (Figure 3). Meanwhile, *Dacrycarpus imbricatus* emerged as the most abundant species in the unburned area (230 individuals/ha). Nevertheless, based on IVI, *E. urophylla* was the dominant species at both sites (Table 3). Two tree species, i.e., *Cyathea contaminans* and *Euodia macrophylla* were only found in the unburned area.

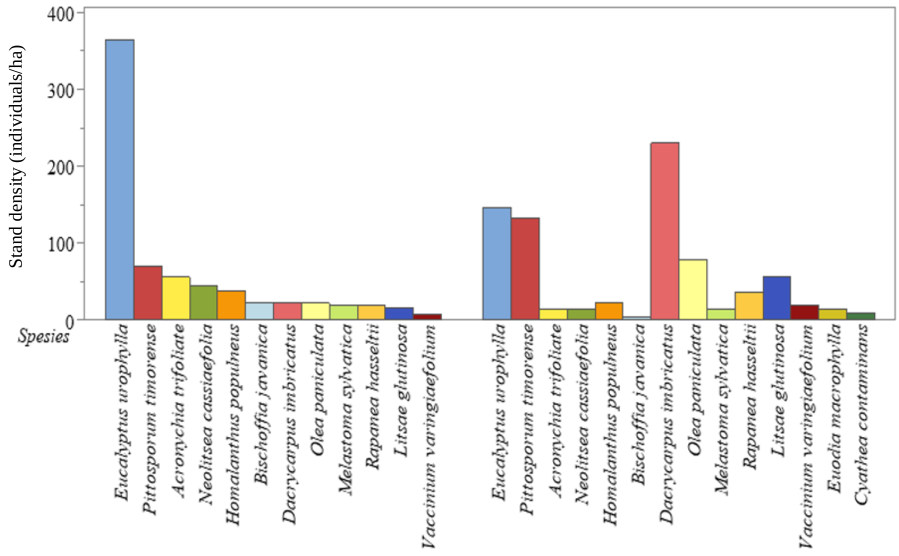

Figure 3. Stand density (individuals/ha) of tree vegetation in burned and unburned areas

Table 3. The Importance Value Index (IVI) of the most important species in burned and unburned site

Spesies	RDi (%)	RFi (%)	RDo (%)	IVI (%)
Burned Site				
Eucalyptus urophylla	51.85	32.89	92.31	177.05
Pittosporum timorense	9.97	14.47	0.53	24.98
Acronychia trifoliate	7.98	11.84	1.06	20.87
Neolitsea cassiaefolia	6.27	7.24	0.13	13.64
Homalanthus populneus	5.41	7.89	0.09	13.40
Dacrycarpus imbricatus	3.13	5.92	2.45	11.51
Olea paniculata	3.13	3.29	1.44	7.87
Acalypha caturus	2.85	4.61	0.02	7.48
Litsae glutinosa	2.28	4.61	0.02	6.91
Bischoffia javanica	3.13	2.63	1.09	6.86
Rapanea hasseltii	2.85	3.29	0.45	6.59
Vaccinium varingiaefolium	1.14	1.32	0.40	2.86
Unburned site				
Eucalyptus urophylla	18.48	21.96	75.25	115.70
Dacrycarpus imbricatus	29.11	21.50	17.56	68.17
Pittosporum timorense	16.71	15.42	0.57	32.70
Olea paniculata	9.87	10.28	3.26	23.41
Litsae glutinosa	7.09	8.88	0.63	16.59
Rapanea hasseltii	4.56	4.21	0.49	9.25
Vaccinium varingiaefolium	2.53	3.27	0.46	6.27
Homalanthus populneus	2.78	3.27	0.13	6.19
Euodia macrophylla	1.77	2.34	0.75	4.86
Neolitsea cassiaefolia	1.77	2.34	0.56	4.67
Acalypha caturus	1.77	2.34	0.08	4.19
Acronychia trifoliate	1.77	1.87	0.10	3.75
Cyathea contaminans	1.27	1.87	0.07	3.20
Bischoffia javanica	0.51	0.47	0.08	1.05

When comparing the size class distribution of *E. urophylla* to "other species", a pattern was observed. There was a higher density of *E. urophylla* in small size classes (Figure 4) in burned sites, indicating a higher regeneration capability under fire-affected conditions. Meanwhile, in the unburned sites, the stand density in the low and medium DBH classes was dominated by "other species" (Figure 4). The Chi-square test showed a statistically significant difference in the DBH class distribution between *Eucalyptus urophylla* and "other species" in both burned and unburned locations (χ^2=870.756; df=27; p<0.001).

3.2 Condition of seed rain

As previously mentioned several traps were lost due to theft or damaged by extreme weather. At the time of the last sampling (S12), only 14 seed traps were still functional—6 of which were located in the burned area and 8 in the unburned area. Data from the 14 remaining traps were used for seed rain analysis, since they were considered representative and could consistently record seed deposition dynamics throughout twelve sampling periods. Four seed species were identified and present at both sites, i.e., *E. urophylla*, *Olea paniculata*, *Pittosporum timorense*, and *Rapanea hasseltii***.** The species composition, seed quantities, and seed density in each area are presented in Table 4.

From first (S01) to last (S12) sampling events in 14 seed traps, *E. urophylla* seeds had the highest density at both study sites (Table 4). The highest seed density was recorded in the last sampling period at the burned site (Figure 5). In contrast, the lowest density—indicated by the absence of seeds in the trap—was recorded in the first sample at the unburned site (Figure 5). The high density of *E. urophylla* seeds observed in both area was analysed further to explore differences in seed distribution between the two sites. The Mann-Whitney test revealed that the density of *E. urophylla* seeds between burned and unburned areas differs significantly (p=0.046). Figure 6 presents seed density data *E. urophylla* in three seed categories.

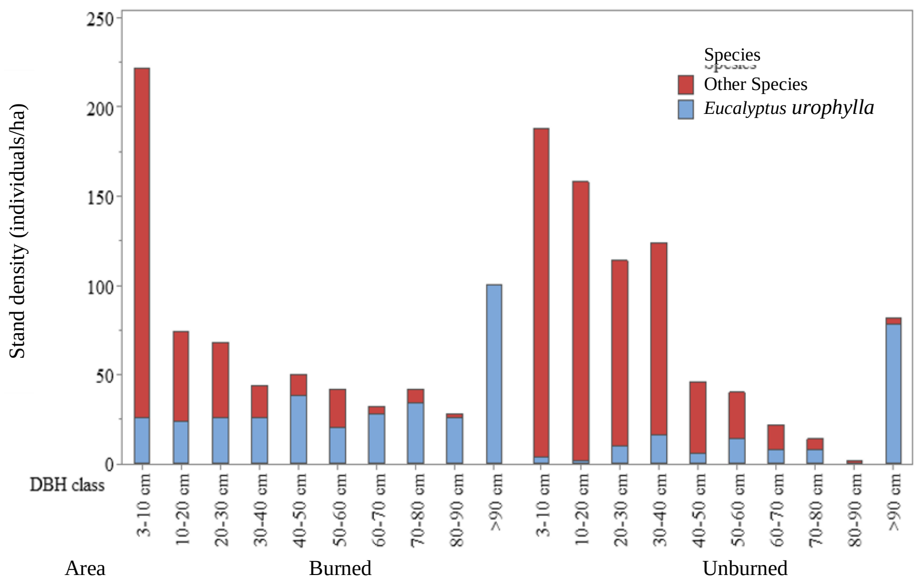

Figure 4. The DBH class distribution of *E. urophylla* and other species in burned and unburned areas

Table 4. The seed rain captured through twelve sampling periods in each sampling area

Spesies	Burned area		Unburned area	
	Quantities (seed)	Seed density (seed/m²)	Quantities (seed)	Seed density (seed/m²)
Eucalyptus urophylla	435	369,4	314	200
Olea paniculata	2	1,7	1	0,6
Pittosporum timorense	14	11,9	20	12,7
Rapanea hasseltii	3	2,5	12	7,6

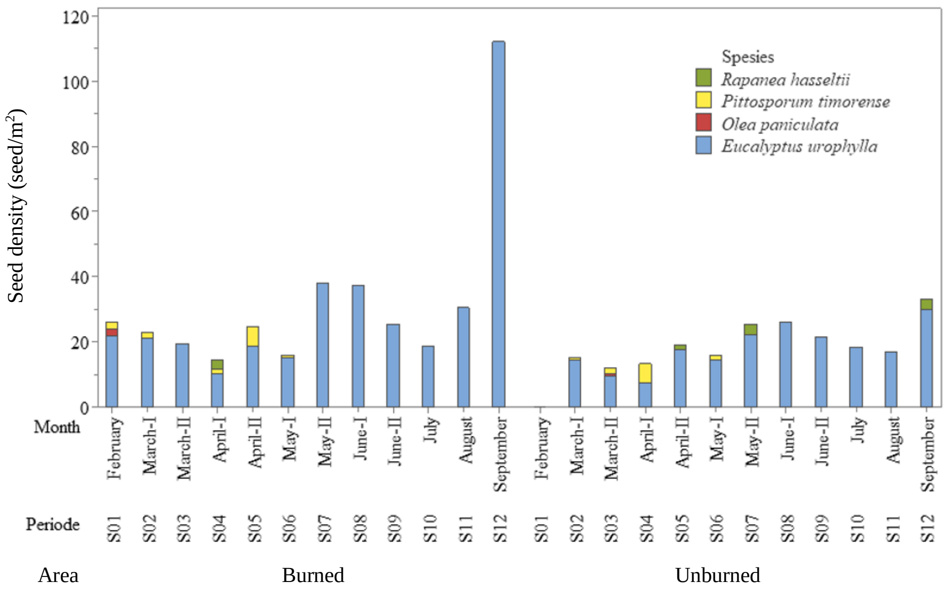

Figure 5. The seed density found in 14 seed traps (six traps in the burned area and eight in the unburned area) in each collection period

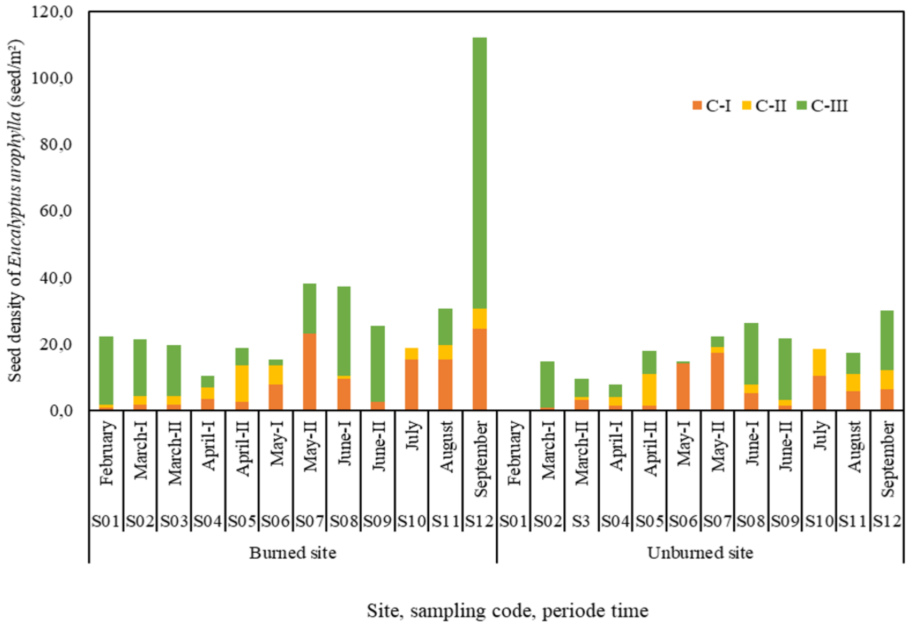

Figure 6. The seed density (seeds/m²) of *E. urophylla* based on their quality categories (C I, CII, or CIII) (Note: Category I (CI): Damaged or rotten fruits or seeds; Category II (C II): Fruits or seeds that were intact, ripe, and had no damage or decay; Category III (C III): Fruits or seeds that are young, small, and immature but not damaged or rotten.)

The Kruskal-Wallis test revealed a statistically significant difference among *E. urophylla* seed categories in the burned sites (p=0.029), indicating a non-uniform seed distribution. Category C-III, comprising small and physiologically immature seeds, exhibited the highest density relative to the other categories. In contrast, no significant difference was detected among *E. urophylla* seed categories in the unburned sites (p=0.241), suggesting a more homogeneous distribution pattern. On the other hand, seeds from Category C-II were the most abundant in the fifth sampling period (April-May), both in burned areas (11.0 seeds/m^2) and unburned areas (9.6 seeds/m^2). These seeds are believed to have natural regeneration potential.

3.3 Relationship among seed rain and vegetation

Eucalyptus urophylla exhibited the highest density in both vegetation and seed rain at both studied areas (Figure 7), suggesting that most of the *E. urophylla* seeds captured the seed rain originated from local vegetation, specifically mature trees surrounding the seed traps. Its highest stand density was found in the burned site, reaching 346 soil/ha. Similarly, the seed density of this species was also highest in the burned area (369.4 seeds/m^2). In the unburned site, although *E. urophylla* did not reach the highest stand density, it still showed the highest seed density (200 seeds/m^2) among other species. In contrast, *D. imbricatus*, which had the highest stand density in the unburned site, did not produce any seeds captured in the seed traps (Figure 7). The calculated Spearman correlation showed no correlation between stand density and seed density in the burned and unburned areas (Table 5).

Table 5. Spearman correlation between stand density and seed density in the burned and unburned site

Site	Variabel 1	Variabel 2	Correlation	p-value
Burned site	Stand density (individual/ha)	Seed density (seed/m²)	0..434	0.158
Unburned site	Stand density (individual/ha)	Seed density (seed/m²)	0.610	0.021

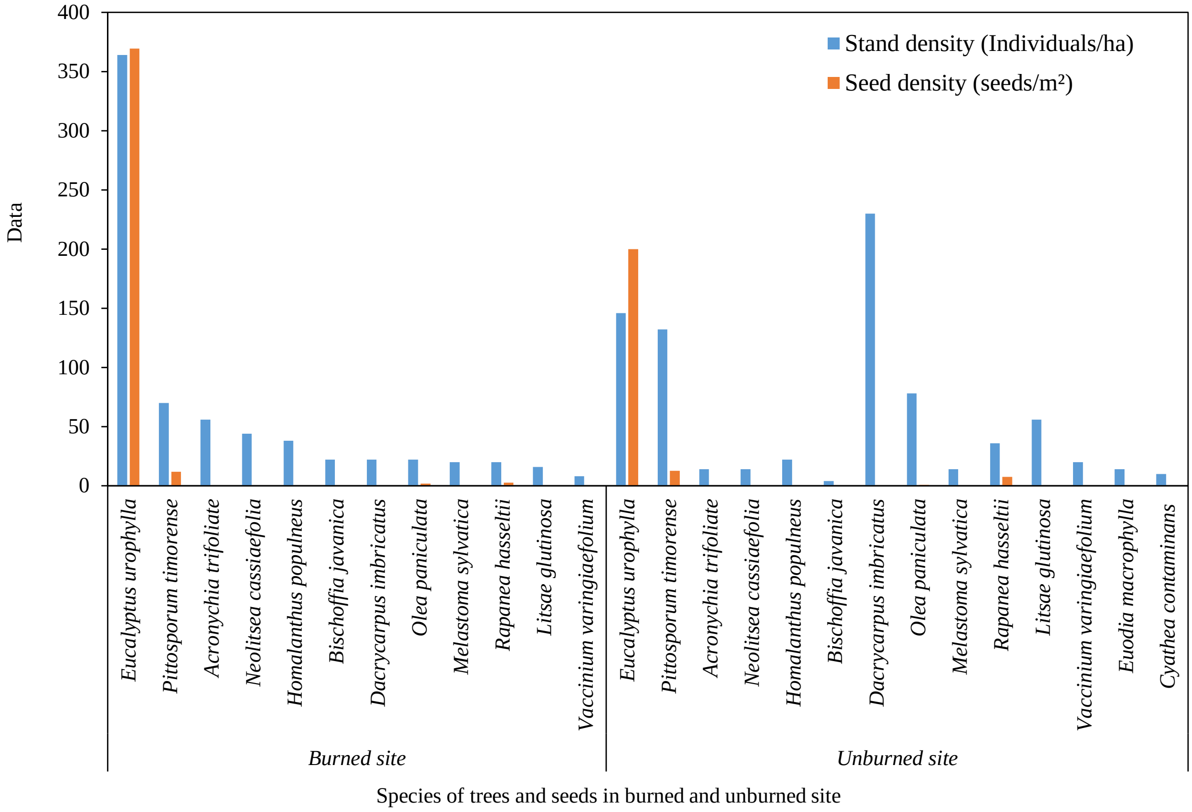

Figure 7. The density of trees and seeds of different species found in burned and unburned areas

The Shannon-Wiener index for vegetation at the unburned area indicated moderate diversity (H'=2.09), while the burned area had a lower index value (H'=1.76). Meanwhile, the Shannon-Wiener index for seed rain at both the burned (H'=0.21) and unburned (H' =0.39) area showed very low values. Additionally, by using rainfall data for the Fatumnasi village area, we analysed the relationship between rainfall and seed density in both sites (Figure 8).

Spearman correlation was used to analyse the correlation between rainfall and seed density in the burned and unburned area (Table 6).

Spearman's correlation analysis shows that when rainfall increases, seed density tends to decrease, although not strongly (r=-0.490), but this correlation is not significant (p-value>0.05). Meanwhile, in the unburned location, it was found that the higher the rainfall, the lower the seed density. This may indicate a decrease in the number of seeds falling into the traps.

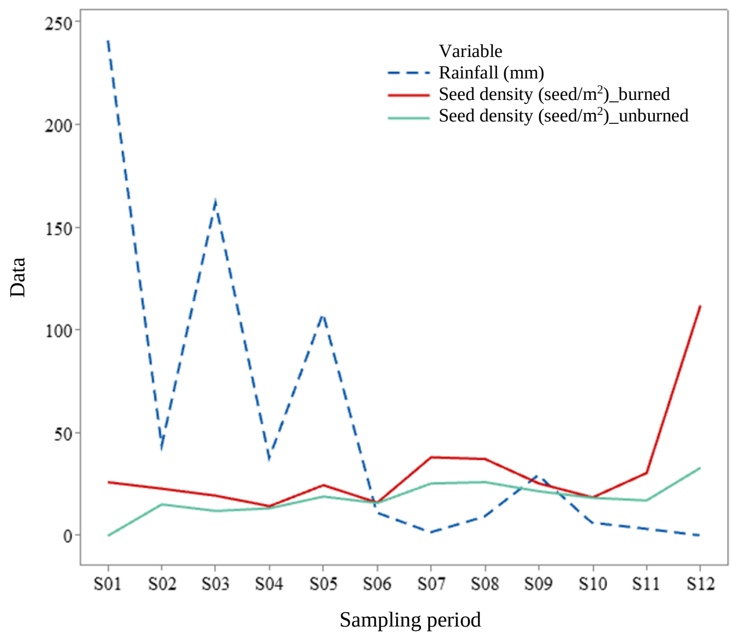

Figure 8. The relationship between rainfall in Fatumnasi Village and seed density in burned and unburned sites

Table 6. Spearman correlation between rainfall and seed density in the burned and unburned site

Site	Variabel 1	Variabel 2	Correlation	p-value
Burned site	Rainfall (mm)	Seed density (seed/m²)	- 0.490	0.106
Unburned site	Rainfall (mm)	Seed density (seed/m²)	- 0.748	0.005

4. DISCUSSION

This study found no significant difference in vegetation density between burned and unburned sites, indicating that fire disturbance did not directly affect overall vegetation density. A possible explanation is likely the severity and intensity of the fire, as well as the natural regeneration capacity of dominant species or the introduction of pioneer species that quickly colonise post-fire sites, allowing vegetation density to recover rapidly. These findings are consistent with a study in the tropical mountain forests of Vietnam, which found that although burned plots showed lower species diversity, tree density, and basal area than unburned areas, their vegetation showed signs of recovery towards unburned conditions within just a few years, especially if the fire was of low to moderate intensity and the burned areas located near the edge of unburned forest. (Trang et al., 2023).

The results of this study showed that *E. urophylla* has a significant ecological role in the burned and unburned sites. Its high IVI indicates that *E. urophylla* is a dominant species with the ability to adapt and dominate post-fire vegetation structure and an important role in the early successional phase and ecosystem restoration. This result suggests that forest fires have influenced the structure of plant communities, potentially leading to the dominance of pioneer or fire-resistant species in burned areas. The forest fires that occurred in tropical forests in South India have also indicated an impact on vegetation dynamics, forest structure and regeneration (Sathya and Jayakumar, 2017). The dominance of *E. urophylla* in the largest class in both area are likely related to its ability to withstand fire. Trees with larger-diameter stems generally have thicker bark, which provides greater resilience against fire compared to those with smaller-diameter stems (Pausas, 2015). In unburned areas, *E. urophylla* has few small trees, indicating future replacement. However, these areas are more diverse, so careful forest fire management is necessary to make it beneficial for the maintenance of *E. urophylla*.

In this study, seed production from trees in both sites was resilient and no longer affected by fire events. The seed rain in both study areas was dominated by *E. urophylla*, indicating that most of the distributed seeds originated from surrounding mature forests of this species. Although, *E. urophylla* is an important component of the vegetation in Mutis forest, the dominance of this species is stronger in burned area. Meanwhile, in the unburned area, *D. imbricatus* was found co-dominants with *E. urophylla*. While fires occur almost every year in Mutis forest, the fire intensity should be considered when determine its the impact on vegetation and seed rain. We found that the diversity of vegetation and the seed potential for regeneration were very low. Similar findings have been reported in studies on forests dominated by Eucalyptus (Standish et al., 2007; Zivec and Johnston-Bates, 2024). However, because of limitations in this study, which only monitored seed rain over a short time period, long-term studies on seed rain and vegetation dynamics will be necessary to provide more information on this and to monitor the effects of climate change on the vegetation community.

The Mutis forest area is a diverse forest dominated by *E. urophylla*. However, the natural regeneration potential of *E. urophylla* is low, as indicated by the proportion of individuals with small DBH (3-10 cm), which is much smaller than that of large DBH (DBH>50 cm). Therefore, active restoration efforts in the form of planting Eucalyptus as the dominant species are needed. The post-fire restoration effort has also been implemented in many places (Scheper et al., 2021; Sorenson et al., 2025; Verma and Jayakumar, 2015). With the change in the area's status from Nature Reserve to National Park, such efforts are feasible if carried out in designated zones. To support the planting of *E. urophylla*, seeds are required. This study recommends collecting seeds from April to May, cultivating seedlings from these seeds, and planting *E. urophylla* as the dominant species. On the other hand, several preventive strategies for managing forest fires are crucial, for instance, implementing stricter law enforcement on intentional firesetting in surrounding forest areas and implementing payment for ecosystem services (PES). The payments for ecosystem services have been already implemented in some regions (Ottaviani, 2011). Collaboration among all stakeholders, including the government and local communities, is essential for the success of conservation efforts.

5. CONCLUSION

Fire is a recurring disturbance in the Mutis forest area, which occurrs almost every year. *E. urophylla* was identified as the dominant tree species as well as seed production in burned and unburned areas, suggesting that seed production could still occur despite the fires at the current fire intensity. However, more fire intensity needs to be anticipated because if fires coincide during the early stages of *E. urophylla* seed development during the dry season, this could threaten natural seed regeneration. Therefore, further study is needed to understand the mechanisms and mitigation strategies.

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AUTHOR CONTRIBUTIONS

Conceptualization, Damanik DER, Choesin DN, Sulistyawati E; Methodology, Damanik DER, Choesin DN, Sulistyawati E; Software, Damanik DER; Validation, D Choesin DN, Sulistyawati E; Formal Analysis, Damanik DER, Choesin DN, Sulistyawati E; Investigation, Damanik DER, Sulistyawati E; Resources, Damanik DER; Data Curation, Damanik DER; Writing-Original Draft Preparation, Damanik DER; Writing-Review and Editing, Damanik DER, Choesin DN, Sulistyawati E; Visualization, Damanik DER; Supervision, Choesin DN, Sulistyawati E.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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