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Full Length Research Article

Stand Structure Dynamic of Logged Over Forest after Selective Timber Harvesting in Boven Digoel, Papua

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ABSTRACT

Logged-over natural forest has a different stand structure and composition from primary natural forest due to logging activities. This study aimed to examine forest dynamics (upgrowth, ingrowth, and mortality) of the logged-over forest in PT. Tunas Timber Lestari (TTL) Papua in both stands with and without treatments. The data used in this study were based on the measurement in the Permanent Measurement Plots (PUP) for ten years. This study grouped data into five diameter classes of 10 cm intervals and three wood species groups (meranti timber, mixed timber, and non-commercial timber). Data analysis was carried out by forming a stand structure model and calculating the rate of ingrowth, upgrowth, and mortality. The stand structure model for each species group in stands with treatment had a significant R^2 value compared to those without treatment. The average ingrowth rate in the stands with treatment was smaller than without treatment. The values of upgrowth varied with the increase in diameter classes for both stands with and without treatments. The mortality rate in stands without treatment tended to be higher, especially in mixed timber and non-commercial timber groups. In contrast, in the meranti timber group, the mortality rate mostly occurred in the stands with treatment. The stand structure models resulting in this study can be used as important information in determining appropriate silvicultural options for forest stands.

1. Introduction

Most of the natural forest areas in Indonesia are logged-over forest areas that have entered the second rotation (Directorate General of Forestry Planning Republic of Indonesia 2011). Logged-over areas are natural forest areas that have been selectively logged, and the areas usually leave remaining stands with a natural stand structure that allows them to grow or recover into the stands suitable for logging at the next cutting rotation (Muhdin 2012). The stand structure dynamics in natural forest is difficult to predict because the species composition varies greatly in age and diameter class. The dynamics of the strand structure can be constructed through an analysis of the components of stand growth, such as ingrowth, upgrowth, and mortality (Bettinger 2017).

The growth dynamics of forest stands can describe the number of trees available based on diameter class and how long it takes to achieve regeneration into sustainable conditions (Muhdin 2012; Susanty et al. 2013). Stand structure is an important component in analyzing natural forest stands to explain the stand dynamics in tropical forests (Gonçalves 2022). Several studies of stand growth have been conducted (Brunner et al. 2020; Kuswandi 2017; Wahyudi 2012).

The results of the analysis of growth components can be used as basic information in determining appropriate silvicultural measures in a forest stand. Krisnawati and Wahjono (2010) reported that logged-over forests in West Kalimantan with silvicultural treatment have a higher growth rate than those without treatment. Another study on logged-over forests in Papua (Kuswandi 2014) showed the opposite, showing the growth rate of trees in stands with silvicultural treatment was slower than in stands without silvicultural treatment. Under the Indonesian Selective Logging and Planting (*Tebang Pilih Tanam Indonesia*/TPTI) regulations, forest management units are required to cut all undergrowth and climb plants for several years after logging. This activity is called liberation and thinning. It aims to control the aggressive weeds or undergrowth and accelerate forest regeneration. However, Kuswandi (2014) explained that this activity had a negative effect on some species of woody plants and trees. Therefore, it impacted the rate of ingrowth and regeneration of forest stands.

A previous study on the effect of silvicultural measures on logged-over forest stands in Papua has been investigated (Kuswandi 2014). However, the study particularly observed the effect of the stand without paying attention to the effect of silvicultural treatment on tree species groups in each diameter class. The application of silvicultural techniques and the resulting impacts have different effects for each species group; some tree species are susceptible to canopy opening and vice versa. Likewise, the growth rate of each tree species will vary in each diameter class. The growth rate per diameter class and species group are very important in determining the silvicultural technique used so that the stand condition can return to its original state (Aswandi 2005). Therefore, this study aimed to examine the dynamics of stands (upgrowth, ingrowth, and mortality) of logged-over forests in Boven Digoel.

2. Methods

2.1. Research Location

This study was conducted in the Permanent Measurement Plots (PUP) located in the logged-over forest area of PT. Tunas Timber Lestari, Boven Digul Regency, Papua (**Fig. 1**). The PUP area used as the sample was 1 ha (100 m × 100 m) each (Krisnawati et al. 2021) located in the ex-harvesting compartment E55 of the annual work plan 2004. The topography is relatively flat with a slope of 0-8% and an altitude of 20-50 masl. The types of soil found at the study site were ultisol, brown-gray podzolic, red-yellow podzolic, and alluvial. The climate is classified as type A, with an average annual rainfall of 4196 mm. The number of rainy days per month ranges between 11 and 24 days (Tunas Timber Lestari 2017).

2.2. Research Design

2.2.1. Data description

The data used in this study were obtained from PUP measurements in 2004, the ex-harvesting compartment E55 of the annual work plan 2004. The PUP consists of 6 measurement plots (PUs), namely 3 PUs that received treatment in the form of enrichment and liberation both vertically and horizontally (PU 1, 2, 3) and 3 PUs that did not receive any treatment (PU 4, 5, 6). The PUP location was chosen because it represented the diversity of tree species and diameter classes found at the study site. Measurements of the tree circumference in each PU are carried out annually at 1.30 cm above the ground or 20 cm above the buttresses. The PUP data series from observations for 10 years (2005-2015) was used.

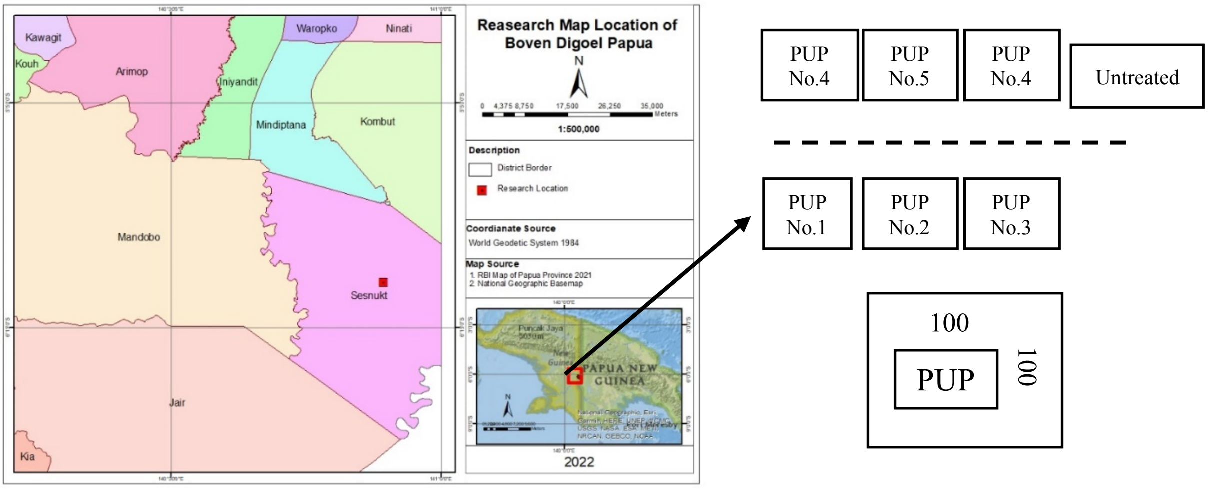


Fig. 1. Research locations and PUP design.

2.2.2. Data collection

PUP data were grouped into three wood species groups: meranti timber group, mixed timber group, and non-commercial timber group. This grouping was done to simplify the diversity of existing species and was observed in accordance with Kepmenhut 163-Kpts-II-2003 concerning the grouping of wood species as the basis for imposing forestry fees. This regulation divided tree species into commercial species group (meranti timber group and mixed timber group) and non-commercial timber group. Tree grouping according to diameter class is done by making five diameter classes (KD) consisting of KD I (10-19.9 cm), KD II (20-29.9 cm), KD III (30-39.9 cm), KD IV (40-49.9 cm) and KD V (≥ 50 cm). The division of data into five diameter classes was to show complex stand structures and representation in forming stand structure models. Then the data was analyzed to determine the rate of ingrowth, upgrowth, mortality, and changes in population size to create a model of the stand structure for each group (Buijks and Haasnoot 2012).

2.2.3. Formation of a stand structure model

The formation of the initial logged-over stand structure model was based on the model (Meyer et al. 1961) with the following equation.

$$N = N0\, e^{-kd} \tag{1}$$

where N is the number of trees per hectare per diameter class, N_0 is a constant, d is the diameter (cm), e is the base logarithm (2.718281828), and k is the rate of the reduction in the number of trees as the diameter class increases.

2.2.4. Calculation of stand dynamics

The calculation of stand dynamics was carried out using the ingrowth, upgrowth, and mortality variables (Kuswandi 2014, 2017).

2.2.4.1. Ingrowth

Ingrowth is the amount added to the number of trees per hectare that fall into the smallest diameter during a certain period. The ingrowth rate in this study was calculated as an additional number of trees that entered KD I (the diameter of 10-19.9 cm) in hectare units. Ingrowth is calculated using the following formula (Kuswandi 2014, 2017):

$$I = \frac{\Sigma \mathrm{rij}}{\Sigma Nij} \times 100\% \tag{2}$$

where *I* is the ingrowth rate, *rij* is the number of new trees entering diameter class *i* and in year *j*, and *Nij* is the number of trees in diameter class *i* and year *j*.

2.2.4.2. Upgrowth

Upgrowth is the number of additional trees per hectare for a certain diameter class that comes from a smaller class over a certain period. The upgrowth rate is obtained from the ratio of the number of trees growing to a larger diameter class with the number of trees in a smaller class. Upgrowth is calculated using the following formula (Kuswandi 2014, 2017):

$$Ui = \frac{\Sigma \mathrm{uij}}{\Sigma Nij} \times 100\% \tag{3}$$

where *Ui* is the upgrowth rate in diameter class *i*, *Uij* is the number of trees rising to diameter class *i* and in year *j*, and *Nij* is the number of trees in diameter class *i* and year *j*.

2.2.4.3. Mortality

Mortality is the number of trees per hectare that die in each diameter class over a certain period. The magnitude of the mortality rate is obtained from the comparison of the number of dead trees with the number of trees in the previous year. Mortality is calculated using the following formula (Kuswandi 2014, 2017):

$$Mi = \frac{\Sigma \mathrm{mij}}{\Sigma Nij} \times 100\% \tag{4}$$

where *Mi* is the mortality rate in diameter class *i*, *mij* is the number of trees that die in diameter class *i* and year *j*, and *Nij* is the number of trees in diameter class *i* and year *j*.

2.3. Stand Density

Stand density is the total number of trees in a certain area and is expressed in hectares (Bettinger et al. 2017).

2.4. Stand Basal Area

The stand basal area is calculated using the equation for the area of a circle, namely (Bettinger et al. 2017).

$$G = \frac{1}{4}\pi D^2 \tag{5}$$

where G is the basal area (cm^2), π is a constant (3.1415), and D is the tree diameter (cm).

3. Results and Discussion

3.1. Stand Structure

Stand structure illustrates the number of trees or tree basal area per hectare in each diameter class. In natural forests, the age of trees in stands is difficult to determine, so the distribution of diameter classes is used to describe the growth of the trees. The distribution of the number of trees in each diameter class varied in stands with and without treatment. The highest number of trees with a diameter class of 10-19 cm in the stand with treatment showed in the meranti timber group, followed by the mixed timber group and non-commercial timber group with the amount of 49.35%, 45.53%, and 53.06%, respectively. Likewise, stands without treatment with the highest number of trees were in the 10-19 cm diameter class for the meranti timber group (45.53%), mixed timber group (65.62%), and non-commercial timber group (68.85%).

The stand structure in the stands with and without the treatment was composed of relatively more small trees than trees with diameters above 50 cm (**Fig. 2**). The results showed that the distribution of trees would decrease in the large diameter class, which forms an inverted J-shaped curve following a negative exponential pattern. In tropical natural forests, the stand structure will generally decrease with increasing diameter class (Abdurachman and Susanty 2014; Heriyanto et al. 2020; Indrajaya 2015; Sukarna et al. 2022).

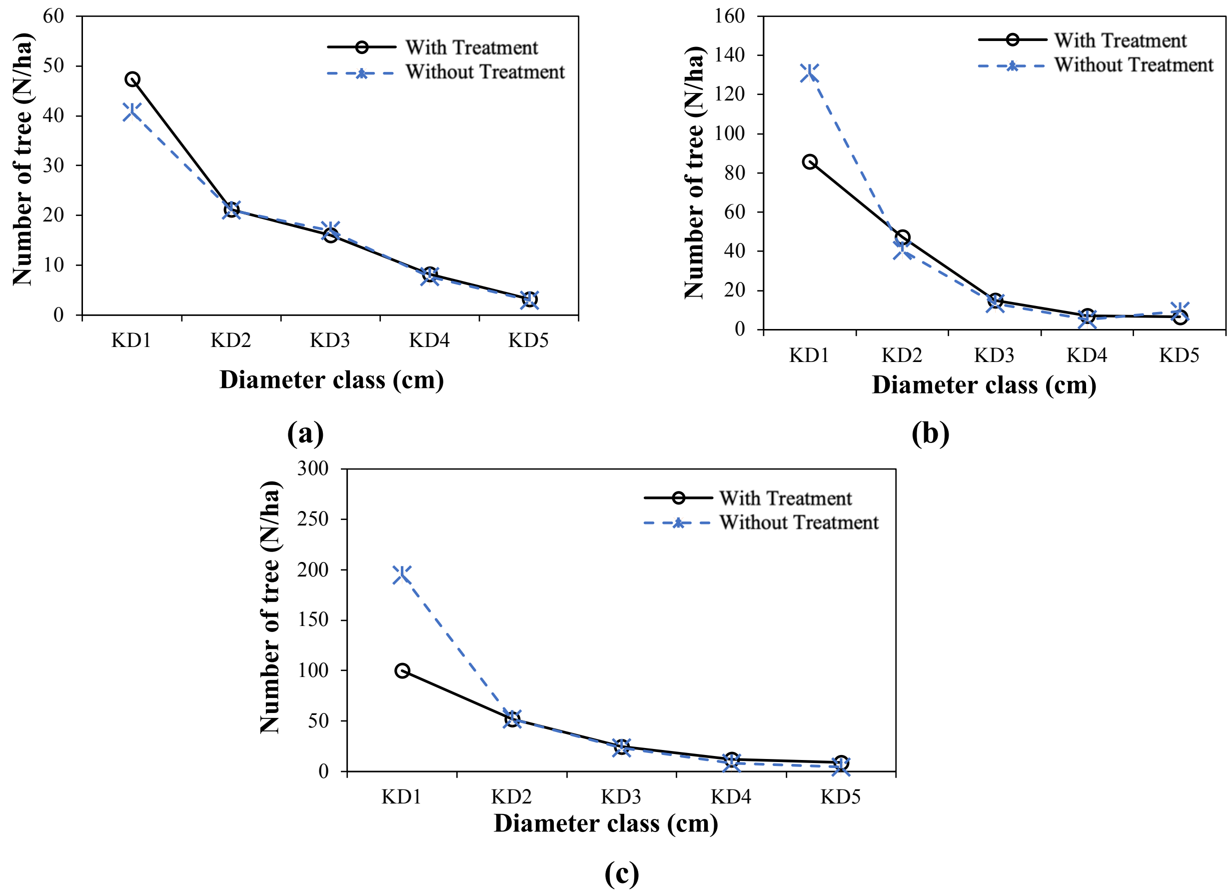
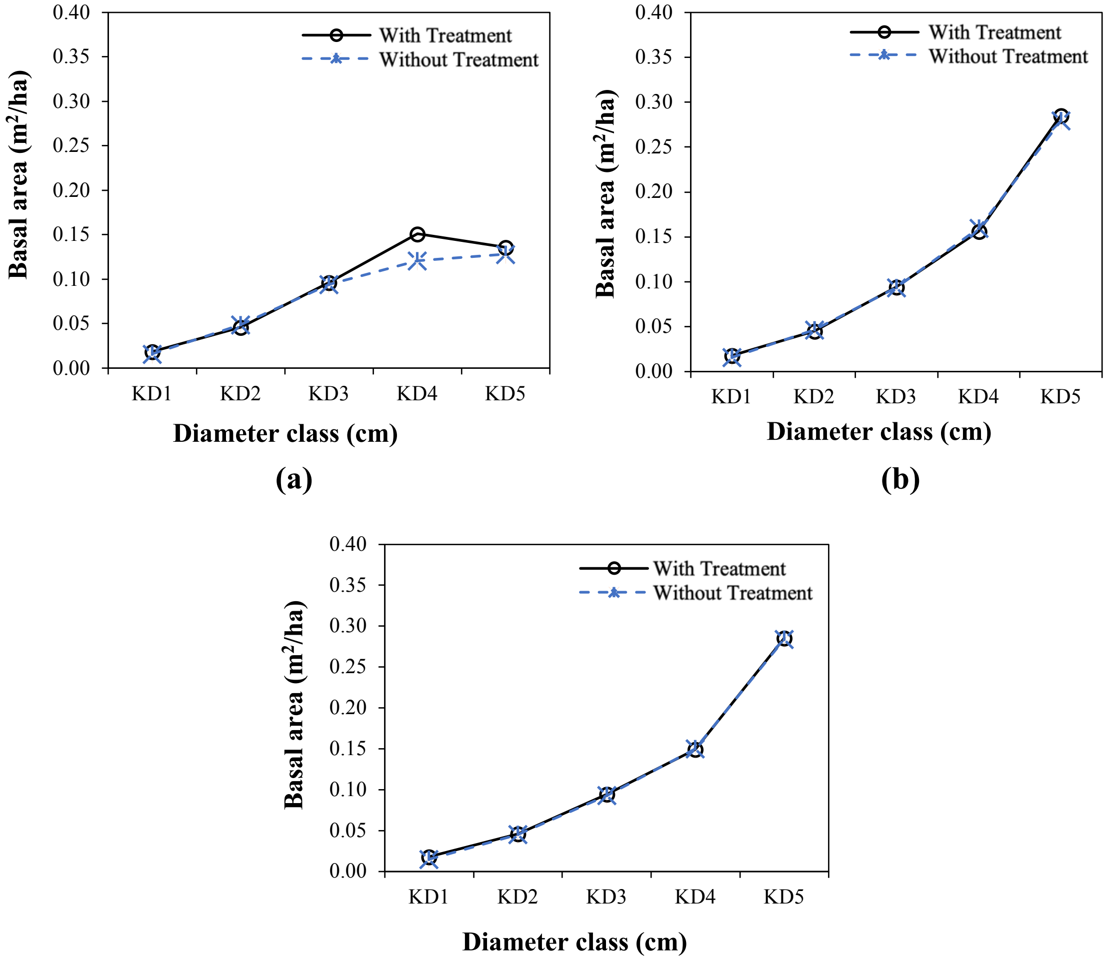


Fig. 2. The average number of trees. (a) meranti timber group, (b) non-commercial timber group, and (c) mixed timber group.

The basal area value in the mixed timber and non-commercial timber groups increased as the diameter class increased. In contrast, the basal area in the meranti timber group increased in the diameter class of 40-49 cm and then decreased in the diameter class of ≥ 50 cm (**Fig. 3**). The result showed that in the meranti timber group, the number of trees with the large diameter class was greater in the diameter class of 40-49 cm. This tendency differs from the mixed timber and non-commercial timber groups, where more trees with large diameters are in the diameter class of ≥ 50 cm. The increase in basal area is in line with the number of trees in each diameter class, where the number of trees decreases in the large diameter class. The dimension often used to predict the growth of a stand is the diameter which correlates with the basal area (Abdurachman and Susanty 2014). Stand basal area describes the sum of the surface area of each living tree, which is a measure of tree density (Bettinger et al. 2017).



(c)

Fig. 3. The average value of the basal area: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.

Based on the distribution of the number of trees in each diameter class, a stand structure model can be made to describe the regeneration capacity of a stand. The stand structure model explains the relationship between tree diameter and the number of trees per hectare (Muhdin et al. 2008). In general, the stand structure model that was formed showed a coefficient of determination (R^2) between 89.90% and 97.80% for the meranti timber group, 78.60% to 96.30% for the mixed-timber group, and 95.70% to 99.10% for the non-commercial timber group (**Table 1**). A stand structure model with a negative exponential equation has been used in logged-over natural forests in several locations in Indonesia with a fairly high coefficient of determination (Krisnawati et al. 2008; Marwa 2009; Muhdin et al. 2008).

Table 1. Structural models of species groups at 3 years of measurement

Groups	Years	The stands structural models ($N = N_o e^{-kD}$)		
		N_0	k	R^2
Stands with treatment				
Meranti	2005 (t+1)	238.90	-0.75	0.940
	2010 (t+6)	176.22	-0.65	0.978
	2015 (t+11)	102.64	-0.50	0.899
Mixed timber	2005 (t+1)	433.90	-0.80	0.963
	2010 (t+6)	320.82	-0.70	0.920
	2015 (t+11)	259.59	-0.64	0.915
Non-commercial timber	2005 (t+1)	199.20	-0.69	0.957
	2010 (t+6)	179.32	-0.63	0.982
	2015 (t+11)	141.19	-0.53	0.979
Stands without treatment				
Meranti	2005 (t+1)	165.45	-0.69	0.948
	2010 (t+6)	151.57	-0.62	0.957
	2015 (t+11)	161.29	-0.61	0.954
Mixed timber	2005 (t+1)	264.40	-0.65	0.801
	2010 (t+6)	387.45	-0.74	0.786
	2015 (t+11)	485.87	-0.76	0.869
Non-commercial timber	2005 (t+1)	287.26	-0.90	0.986
	2010 (t+6)	408.75	-0.935	0.968
	2015 (t+11)	495.44	-0.941	0.991

Notes: *No* is a constant, *k* is the rate of the decrease in the number of trees, and R^2 is the coefficient of determination.

The values of N_0 and the rate of the decrease in the number of trees as the diameter class increases differ in each stand and species group (**Table 1**). The *No* value in treated stands decreased with increasing measurement time for each species group, in contrast to untreated stands, where the N_0 value decreased in 2010 and then rose again in 2015 for the mixed timber and non-commercial species groups. The stand structure model was constructed using the variable diameter as the independent variable. The higher the N_0 value, the greater the number of trees per hectare in the smallest diameter class. Likewise, the greater the value of k, the greater the rate of reduction in the number of trees between diameter classes (Muhdin 2012).

These results showed that stands with the treatment have a trend of decreasing the number of small-diameter trees over time, in contrast to stands without treatment which decreased from the beginning of the year of logging and then increased in 2015. Muhdin (2012) and Krisnawati et al. (2008) stated that a lower value of N_0 showed the number of ingrowth or trees with a small diameter which is small. The rate value of the decrease in the number of trees in stands with treatment decreased in each measurement year for each species group, whereas in stands without treatment tended to fluctuate. A large value of the rate of the decrease in the number of trees describes a sharp decrease in the number of trees as the diameter increases. Conversely, if the value of the rate of the decrease in the number of trees is small, it means that the decrease in the number of trees is not sharp (sloping) (Muhdin 2012; Muhdin et al. 2008; Yandi et al. 2019).

The values of N_0 and the rate of the decrease in the number of trees indicate that the stands with treatment have a trend of the number of small-diameter trees decreasing with time, in contrast to the stands without treatment, which decreased from the beginning of the year of logging and then increased in 2015. The number of small-diameter trees (seedlings) in stands that were left naturally tends to be more abundant than in stands with treatment. The results of this study are different from a study conducted by (Krisnawati and Wahjono 2010), where the growth rate of remaining stands doubled with treatment. Silvicultural treatment, such as maintenance, should positively impact stand growth. The decrease in the number of trees at the seedling and sapling level in treatment stands was thought to be caused by the clearing of the stands, which was too intensive, causing openness and death.

3.2. *Ingrowth Rate*

The ingrowth rate is the proportion of the number of trees in the smallest diameter class. The magnitude of the ingrowth rate in stands with treatment tended to increase from the first year after logging to the fifth year after logging and decreased in the sixth year after logging for the meranti timber, mixed timber, and non-commercial timber groups. Meanwhile, in unthreatened stands, the ingrowth rate increased from the first year of logging to the fourth year after logging and decreased in the fifth year after logging for each species group (**Fig. 4**). The removal of forest covers due to logging activities in logged-over forest stands causes sunlight to enter the stands thereby affecting the growth rate of seedlings. The size of the resulting gaps in standing forests varies with the degree of regeneration (MacIsaac et al. 2006; Zhu et al. 2021).

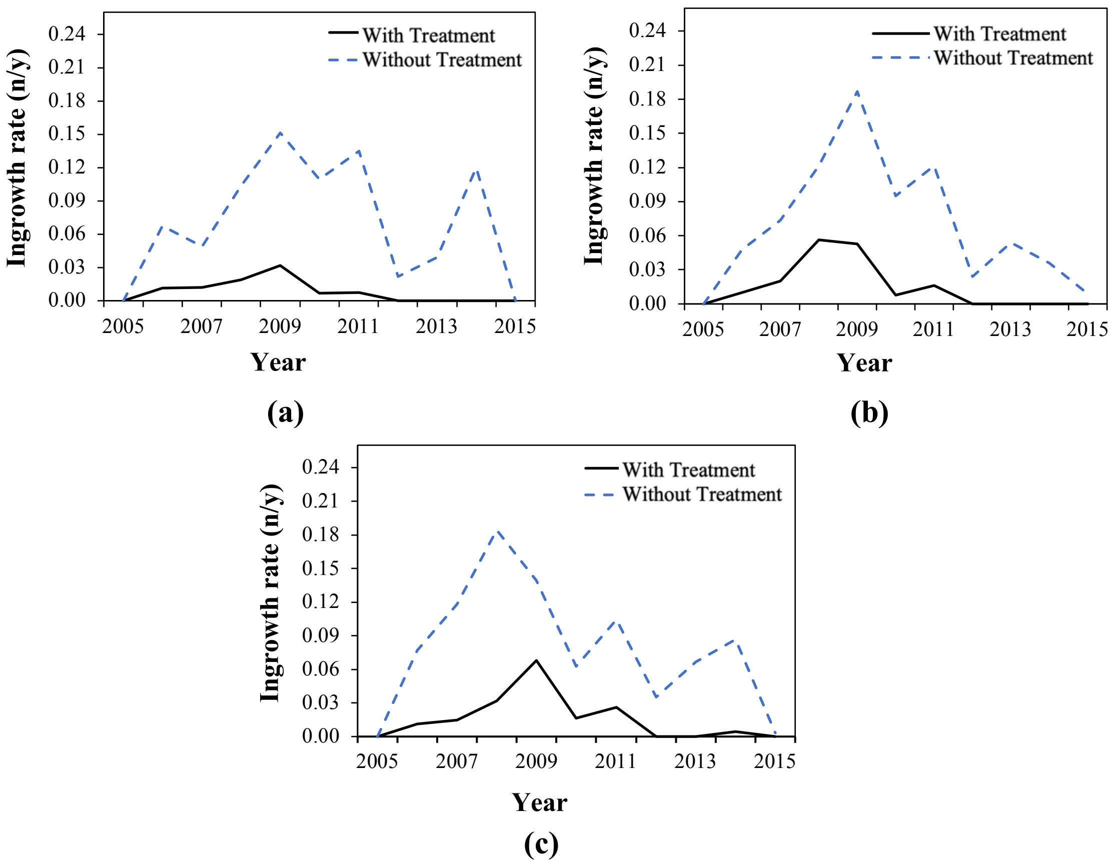


Fig. 4. The average value of the ingrowth rate: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.

The highest ingrowth rate in treatment stands occurred in the fifth year after logging at 3.2% for meranti and 6.8% for non-commercial. Whereas for the mixed timber group, it occurred in the fourth year after logging by 5.3%. The ingrowth rate of the meranti timber group on stands with treatment was lower than that on stands without treatment. The same goes for the mixed timber and non-commercial timber groups. The ingrowth value in stands without treatment tends to be higher than in stands with treatment. This is presumably due to the influence of treatment activities on the undergrowth with high intensity, which impacts the regeneration of stands at the seedling level. The number of seedlings lost due to treatment activities will affect the density and ingrowth rate (Krisnawati et al. 2008) stated that the ingrowth of a species is influenced by the abundance or number of trees of the species concerned and the degree of disturbance of the stand. Similar results were shown by Kuswandi (2014), showing the ingrowth values in stands with treatment tended to be lower than in stands left naturally.

3.3. Upgrowth Rate

The upgrowth rate is the number of trees that rise to the next diameter class. The upgrowth rate for each diameter class varies according to the measurement time, species group, and stand location (**Fig. 5** and **Fig. 6**).

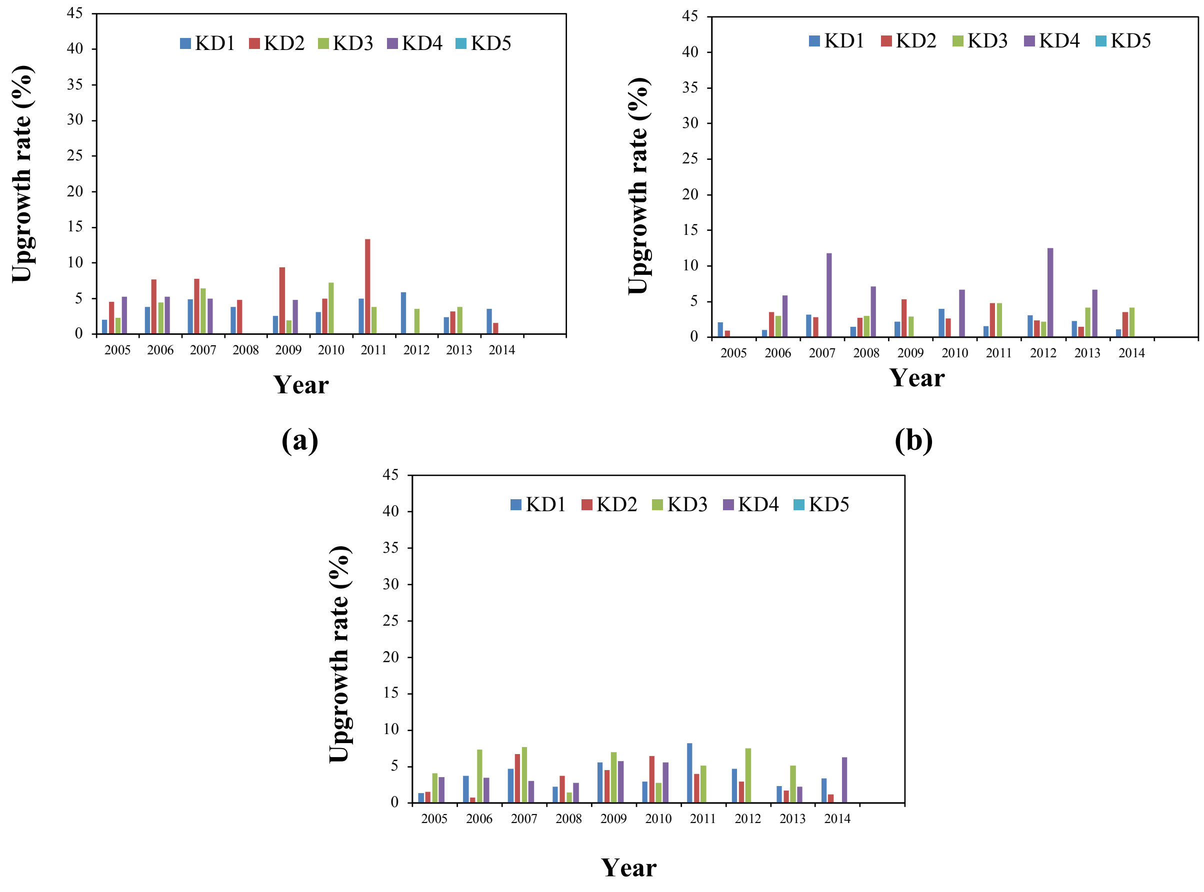


Fig. 5. The upgrowth rate of stands with treatment: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.

The highest upgrowth rate in stands with treatment was found in the diameter class of 10-19 cm to 30-39 cm, while in stands without treatment, there were those in the diameter class of 20-29 cm to 40-49 cm. The magnitude of the upgrowth rate fluctuated in the stand with and without treatment. In the meranti timber group, the upgrowth rate increased in 2011 and decreased for stands with and without treatment.

In the mixed timber group, the upgrowth rate increased in 2007-2008 and then decreased for stands with and without treatment, while in the non-commercial timber group, the upgrowth rate increased in 2007, then decreased for stands with treatment and increased in 2008, then decreased for stands without treatment. The variation in the rate of upgrowth in stands is related to the conditions at each location with different stand densities (Kuswandi et al. 2015). The increasing rate of upgrowth illustrates the phenomenon of the growth of logged-over forests that the upgrowth is higher with the increase in the number of trees. The opening of space after logging encourages tree growth, thereby increasing the density of the stand (Abdurachman and Susanty 2014; Manuri et al. 2017; Pourmajidian et al. 2010). Meanwhile, the decrease in the upgrowth rate was caused by the dominance of large-diameter trees (Kuswandi 2017).

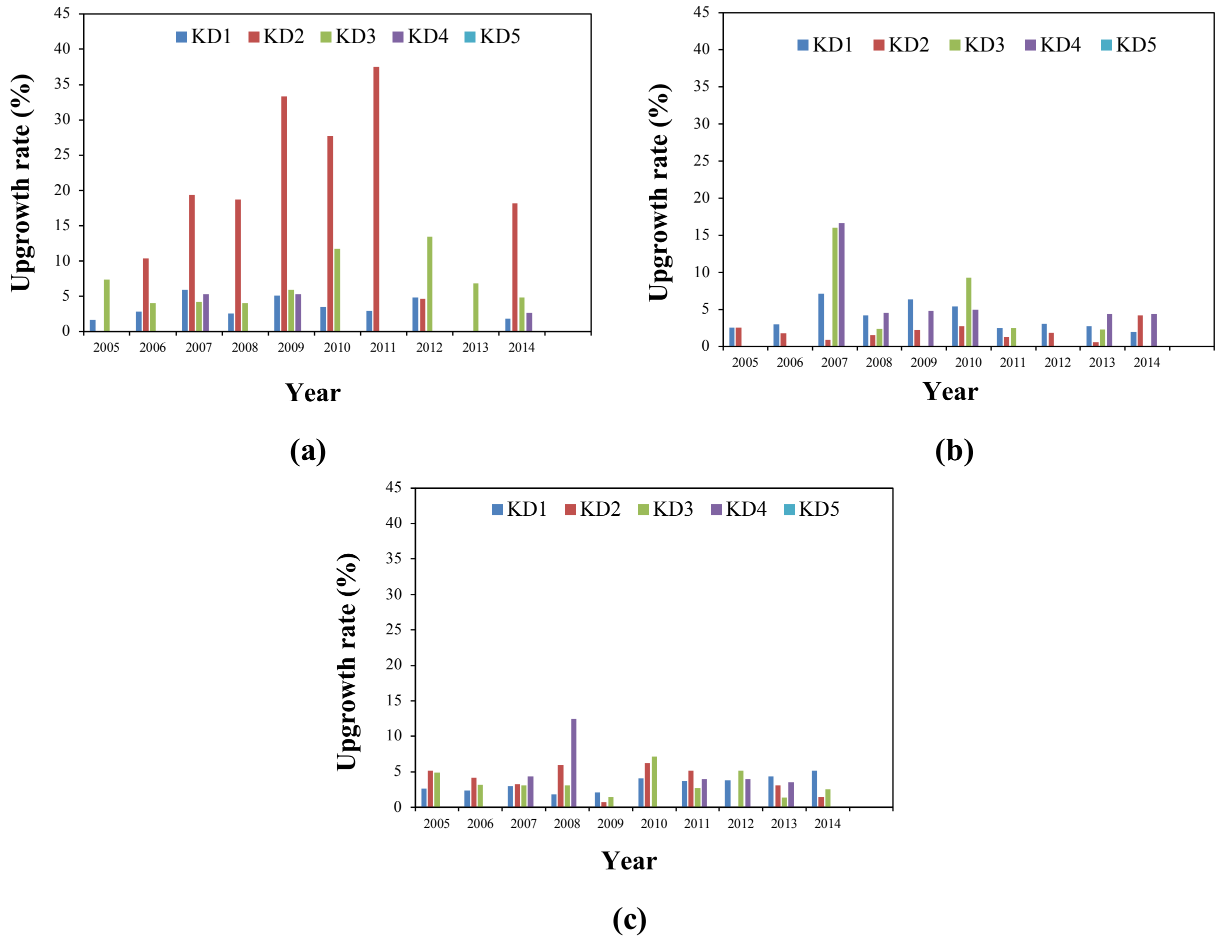
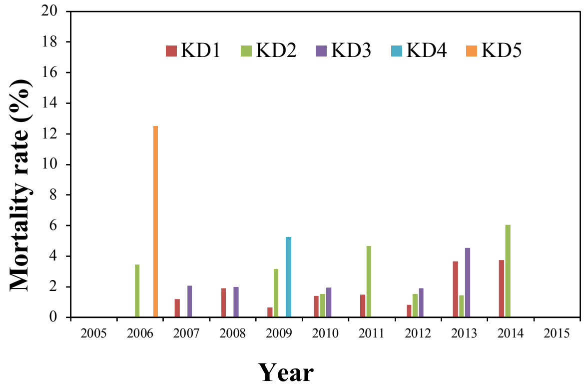


Fig. 6. The upgrowth rate of stands without treatment: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.

3.4. Mortality Rate

The mortality rate is the number of trees that die in each diameter class. Mortality rates varied in the stands with treatment and without treatment for each species group based on the time after logging (**Fig. 7** and **Fig. 8**). The highest mortality in the meranti timber group occurred in the diameter class of ≥ 50 cm in 2006 in the stands with treatment and occurred in the diameter class of 20-29 cm in 2013 in the stands without treatment. In the mixed timber group, the highest mortality occurred in the diameter class of ≥ 50 cm in 2006 for stands with treatment and occurred in the diameter class of 30-39 cm in 2008 for stands without treatment, while in the mixed timber group, the highest mortality occurred in the 20-29 cm diameter class in 2010 for stands with treatment and in the diameter class of 40-49 cm in 2011 for stands without treatment. The variation in mortality rates is influenced by many factors that interact within a stand, making it difficult to predict (Wahyudi 2012).



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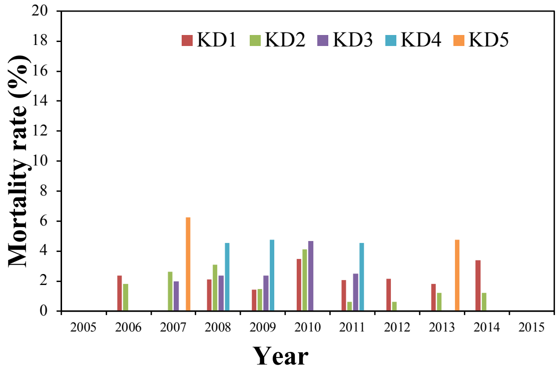

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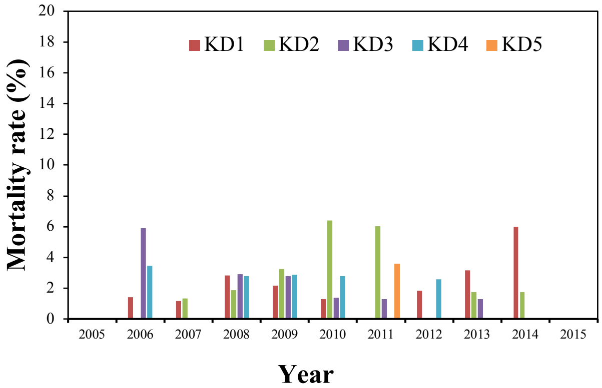

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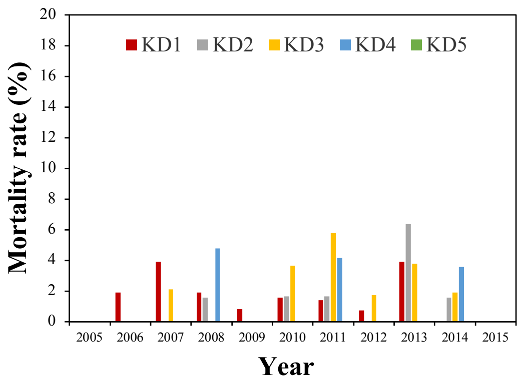
Fig. 7. The mortality rate of stands with treatment: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.



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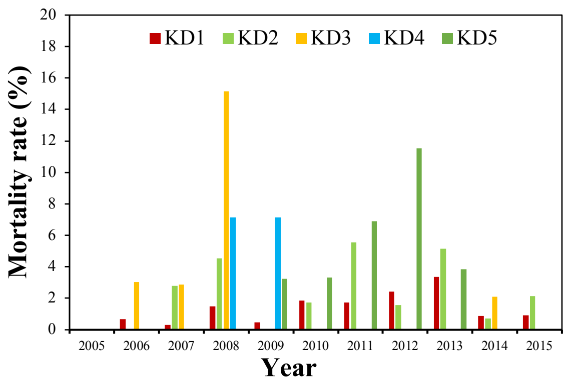

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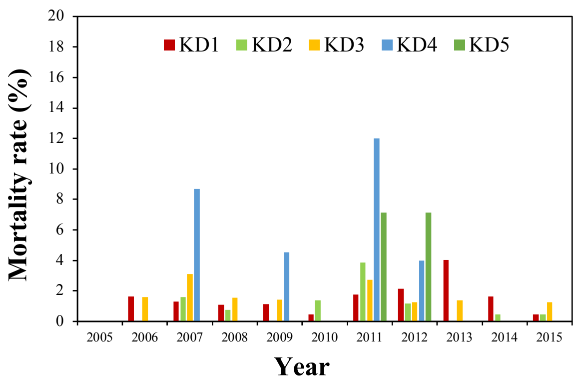

(c)

Fig. 8. The mortality rate of stands without treatment: (a) meranti timber group, (b) mixed timber group, and (c) non-commercial timber group.

On average, the mortality rate in the meranti timber group occurred in the diameter class 20-29 cm (1.99%) in stands with treatment and mostly occurred in the diameter class 30-39 cm (1.72%) in stands without treatment. In the mixed timber group, it mostly occurred in the diameter class of 10-19 cm (1.71%) for stands without treatment and mostly occurred in the diameter class of ≥ 50 cm (2.62%) for stands with treatment. Whereas in the non-commercial timber group, it mostly occurs in diameter class 20-29 cm (2.04%) for stands with treatment and mostly occurs in diameter class 40-49 cm (2.66%) for stands without treatment. Based on these results, it can be seen that mortality in stands without treatment tended to be higher, especially in the mixed timber and non-commercial timber groups. In contrast, the meranti timber group's mortality rate was higher in stands with treatment. Trees in the lowest class with a slower growing trend have a greater chance of dying (Roitman and Vanclay 2015).

Mortality in stands could be caused by several factors, including the impact of logging, stand density, pests, and diseases, as well as the competition within a stand. High felling intensity results in great damage to stands (Mawazin 2013; Muhdi et al. 2012). In the logged-over forest area, logging activities will create spaces in the stands that impact changes in the intensity of environmental factors such as sunlight, climate, humidity, and nutrition. This tendency will affect the growth and death rates of trees, competition, and species composition in a stand. Several studies have shown that pacifying stands affect the growth rate and regeneration of the stand (Gradowski et al. 2010; Johnson et al. 2021; MacIsaac et al. 2006).

4. Conclusions

The stand structure model for the meranti timber group, mixed timber group, and non-commercial group in stands with treatment illustrates that the number of seedlings in treatment stands is lower and tends to decrease each year of observation compared to stands left naturally. Therefore, it impacts stand regeneration to reach the condition beginning. The selection of appropriate treatment actions and intensity is necessary to support the regeneration process of the logged-over forest area where the stand structure has been disturbed by logging activities. In each type of group, the ingrowth rate on stands with treatment was lower than the stands without treatment, while the highest rate of upgrowth occurred at a diameter class of 10-19 cm to 30-39 cm for stands with treatment and the diameter class of 20-29 cm to 40- 49 cm for a stand without treatment. Mortality in stands without treatment tended to be higher, especially in the mixed timber and non-commercial timber groups. In contrast, the meranti timber group showed a higher mortality rate in stands with treatment.

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