FITTING DIAMETER DISTRIBUTIONS OF TROPICAL RAINFORESTS IN VIETNAM BY FIVE PROBABILITY FUNCTIONS

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SUMMARY
This study aims to fit diameter distribution of tropical rainforests in Vietnam and to select suitable continuous distributions. To investigate the diameter distribution of trees in tropical rainforests in Vietnam, data from 20 one – hectare plots were used. The following functions were tested: Beta, Weibull (two- and three-parameter), Lognormal, and Gamma. Parameters of distribution functions were estimated using the maximum likelihood estimation method. The best fits were selected by the Kolmogorov–Smirnov test. The results showed that the diameter distribution of the tropical rainforest was best described by the three – parameter Weibull distribution, followed by Log – normal distribution, while the Weibull 2P model fails in every case to adequately describe these frequency distributions. Estimated parameters μ, β, and α of Weibull 3P distribution ranged from 5.697 – 10.155; 1.029 – 1.606, and 6.921 – 15.234, respectively, while estimated parameters μ and $\boldsymbol{\delta}$ of Log – normal distribution varied from 2.804 – 2.891 and 6.921 – 15.234, respectively. The studied forests showed diameter distributions with decreasing number of trees for larger trees.
Keywords: Continuous distribution, diameter structure, Kolmogorov–Smirnov test, maximum likelihood, tropical rainforest.

1. INTRODUCTION

Diameter distributions are crucial decision–making tools for forest management. They directly affect the choices concerning silvicultural and harvesting stages activities. For instance, timing and intensity of thinning and harvesting, as well as harvesting equipment are dependent on the diameter distributions (Robinson and Hamann, 2011). Furthermore, they are applied as inputs of growth models and sometimes are the subject of growth modeling themselves. Information on current diameter distribution of a forest stand allows prediction of its future structure which provides even better support for sustainable forest management (Vanclay, 1994; Podlaski, 2006).

Beta, Weibull, and Log–normal functions are classic models frequently applied for diameter distribution analysis in tropical forests (Bailey and Dell, 1973; Rennolls *et al.*, 1985; Nanang, 1998; Palahí *et al.*, 2007, Burkhart and Tomé, 2012). However, there are also other investigations highlight the potential of alternative models for predictions that support forest conservation and management (Wang and Rennolls, 2005; Podlaski and Zasada, 2008; Gorgoso-Varela and Rojo-Alboreca, 2014; Lima *et al.*, 2014,; Podlaski and Roesch, 2014). As a result, there are many different probability density functions as the best in fitting diameter of trees. However, the current situation is that there is no clear resolution as to which model is the most suitable for tree distributional modelling (Wang and Rennolls, 2005). There is no theoretical reason why there should exist a best model for all situations. It might be that in one case a particular distribution will be found empirically to give the best fit, whilst in another case another model will be found to be empirically best. The only way in which it is meaningful to talk about the best distributional model is in terms of the most flexible of models in representational terms. Thus, the reason for this research is to compare five distributional models in terms of flexibility and ability on which best fit diameter of trees in tropical rainforests in Vietnam.

2. RESEARCH METHODOLOGY

2.1. Data collection

Stratified random sample method and simple random sampling was applied for the set up sample plots. The data were used from a project "Method of establishing a volume table for standing trees in natural forest, Vietnam"

(Vu Tien Hinh, 2012). Each plot has a square shape (100 m x 100 m) and is divided into twenty five 20 m x 20 m quadrats. From each quadrat, all the tree species having diameter at breast height (DBH) of ≥ 6 cm were recorded by their name and diameters, except the extremely rich forest, DBH of tree species having ≥ 10 cm were recorded by their name and diameters. General plot imformation is reported in Table 1.

Table 1. Provinces, plots and forest states

Province	Plot	Forest state	Province	Plot	Forest state
Tuyen Quang	1	Poor forest	Quang Binh	11	Rich forest
Tuyen Quang	2	Poor forest	Quang Binh	12	Rich forest
Ha Tinh	3	Poor forest	Thua Thien Hue	13	Rich forest
Hoa Binh	4	Poor forest	Thua Thien Hue	14	Rich forest
Hoa Binh	5	Poor forest	Thua Thien Hue	15	Rich forest
Quang Binh	6	Medium forest	Gia Lai	16	Extremely rich forest
Quang Binh	7	Medium forest	Gia Lai	17	Extremely rich forest
Quang Binh	8	Medium forest	Gia Lai	18	Extremely rich forest
Ha Tinh	9	Medium forest	Gia Lai	19	Extremely rich forest
Ha Tinh	10	Medium forest	Gia Lai	20	Extremely rich forest

2.2. Data analysis

2.2.1. Descriptive statistics

Several general information on forest structure were computed for each sample plot, including: mean, standard deviation, variance, min, max, skewness and kurtosis (Machado *et al*. 2009).

2.2.2. Fitting of diameter distribution model

The data were analyzed on several probability density function (pdf), then ranked based on Kolmogorov - Smirnov test. From some previous researches (Carretero and Torres–Alvarez, 2013; Ige et al., 2013; Aigbe, 2014), the following functions were used: Beta, Weibull (two- and three-parameter), Lognormal, and Gamma.

- Beta distribution

This distribution is a continuous distribution and its pdf formula is as follows:

$$\boldsymbol{F(x) = \frac{1}{B(p,q)} \frac{(x-a)^{p-1}(b-x)^{q-1}}{(b-a)^{p+q-1}}}$$

$$\boldsymbol{a \le x \le b},\ p > 0,\ q > 0$$

- Two - parameter Weibull distribution

Weibull distribution was also presented as an cumulative frequency in which a is the starting point and b presents the curve's concavity degree, and c is the curve's factor form or shape index and its mathematical process is as follows:

$$\boldsymbol{f(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}}}$$

For x > 0, α > 0 and β > 0. The parameters α and β are referred to as scale and shape parameter, respectively.

- Three - parameter Weibull distribution

$$f_X(x) = \frac{\alpha}{\beta}\left(\frac{x-\mu}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x-\mu}{\beta}\right)^{\alpha}}$$

$$x > \mu,\ \alpha > 0,\ \beta > 0$$

Where α, β and μ are shape, scale and location parameters, respectively.

- Lognormal distribution

This is continuous distribution and its natural logarithm has a normal distribution

$$\boldsymbol{F(x) = \frac{1}{\sqrt{2\pi\delta x}} exp\left(-\frac{1}{2\delta^2}(Inx - \mu)^2\right)}$$

$$\boldsymbol{\delta > 0, x > 0, 0 < \mu + \infty}$$

- Gamma distribution

This distribution is a continuous distribution and it has a good flexibility and its frequency curve in all modes has a lean towards right.

$$\boldsymbol{F(x) = \frac{x^{\alpha-1}}{\beta T(\alpha)} \exp\left(\frac{-x}{\beta}\right)}$$

$$0 \le x \le +\infty\ \boldsymbol{\alpha, \beta > 0}$$

2.2.3. Estimating parameters for diameter distribution models

The parameters of the distribution are estimated by maximizing the likelihood of the sample.

The method of maximum likelihood is a commonly used procedure for the fitting distribution in forestry because it has very desirable properties. Estimation of the parameters by maximum likelihood has been found to produce consistently better goodness-of-fit statistics compared to the previous methods, but it also puts the greatest demands on the computational resources (Cao, McCarty, 2005).

2.2.4. Test for the goodness of fit

The goodness of fit in different class intervals was carried out using the Kolmogorov–Smirnov test according to the following expression:

$$D_n = \frac{SUP_X\left|Fo_{(x)} - Fe_{(x)}\right|}{n}$$

Where $F_o(x)$ is the accumulate observed frequency;

$Fe_{(x)}$ is the accumulate expected frequency; n is the number of observations; D_n is the calculated D value.

Dn was compared with the value of the Kolmogorov–Smirnov table at a probability level of 95%.

This test was used to check the following hypotheses of the bilateral test:

Null hypothesis: H_0 = the observed diameters follow the proposed distributions

Alternative hypothesis: H_1 = the observed diameters do not follow the proposed distributions.

Parameters for diameter distribution model were estimated using XLSTAT version 2015.5 software.

3. RESULTS AND DISCUSSION

3.1. Descriptive statistics of diameter at breast height

The summary of the descriptive statistics of diameter for tropical rainforests in Vietnam are presented on Table 2.

Table 2. Descriptive statistics of the data sets of diameter at breast height

Variables	**Poor forest**					**Medium forest**				
	Plot1	Plot2	Plot3	Plot4	Plot5	Plot6	Plot7	Plot8	Plot9	Plot10
N*	315	539	431	940	1010	623	362	339	1000	408
Mean	18.6	14.9	13.5	15.3	17.5	16.2	19.9	18.9	16.6	20.3
Std. Deviation	9.8	6.2	6.0	7.7	5.4	9.6	9.5	8.4	10.9	11.3
Variance	95.6	38.4	35.9	58.7	28.9	93.0	91.1	70.3	118.2	126.9
Kurtosis	1.5	1.4	3.0	9.6	3.8	2.4	2.0	0.5	6.3	1.6
Skewness	1.3	1.1	1.7	2.6	1.7	1.5	1.4	0.7	2.2	1.3
Min	6	6.1	7.0	6.8	10.5	6.0	7.0	6.0	6.5	6.0
Max	52	38.2	36.0	56.3	41.5	57.3	54.0	40.0	76.4	60.0
Variables	**Rich forest**					**Extremely rich forest**				
	Plot11	Plot12	Plot13	Plot14	Plot15	Plot16	Plot17	Plot18	Plot19	Plot20
N*	877	825	1079	897	831	485	582	458	560	658
Mean	16.4	17.7	15.7	16.1	16.9	24.3	27.0	25.9	23.2	23.5
Std. Deviation	11.3	10.8	9.5	10.6	10.7	14.8	19.2	15.9	13.8	15.0
Variance	127.6	116.0	90.2	112.1	114.0	218.1	366.9	251.7	191.7	224.6
Kurtosis	3.7	3.7	4.9	6.4	2.3	2.3	3.8	1.4	3.1	4.0
Skewness	1.9	1.8	2.0	2.2	1.5	1.6	1.9	1.4	1.8	1.9
Min	6.0	6.0	6.0	6.1	6.1	10.2	10.2	10.2	10.2	10.2
Max	68.0	68.0	60.0	73.2	63.7	82.8	116.2	85.3	83.4	106.6

N: Number of trees per hectar*

The highest and lowest dbh values found were 25.9 cm and 13.5 cm, respectively (Table 2). The max DBH came from plot 20 in the extremely rich forest. The highest tree densities were counted in plot 13 of the rich forest, whereas the lowest was observed in the plot 1 of the poor forest. Positive kurtosis values imply that diameter distributions are flatter than the normal curve. Skewness was shown positive distributions since the diameter distributions are located on the left side. This pattern means that the tails of diameter distribution extend to the right side or other words, means that considerable numbers of trees concentrate in the lower diameter classes (Gadow, 1983).

3.2. Diameter distribution model

The summary of the goodness of fit of diameter distribution functions for tropical rainforest in Vietnam are presented on Table 3.

Table 3. Summary of goodness of fit of distribution functions for tropical rainforest in Vietnam

Distribution	Poor forest					Medium forest				
	p-value					p-value				
	Plot1	Plot2	Plot3	Plot4	Plot5	Plot6	Plot7	Plot8	Plot9	Plot10
Beta	0.006	0.150	0.011	0.004	0.064	<0.0001	0.0002	0.009	<0.0001	0.024
Weibull 2P	0.011	0.022	<0.0001	0.006	0.013	<0.0001	0.001	0.010	<0.0001	0.043
Weibull 3P	0.090	0.697	0.369	0.114	0.253	0.062	0.091	0.138	0.200	0.255
Lognormal	0.320	0.374	0.028	0.080	0.104	<0.0001	0.100	0.305	<0.0001	0.257
Gamma	0.095	0.280	0.001	0.025	0.072	<0.0001	0.015	0.128	<0.0001	0.135
Distribution	**Rich forest**					**Extremely rich forest**				
	p-value					p-value				
	Plot11	Plot12	Plot13	Plot14	Plot15	Plot16	Plot17	Plot18	Plot19	Plot20
Beta	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.001	<0.0001	0.002	<0.0001	<0.0001
Weibull 2P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Weibull 3P	0.064	0.400	0.001	0.052	0.061	0.507	0.500	0.600	0.162	0.006
Lognormal	0.0002	0.001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.001	<0.0001	<0.0001
Gamma	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

The Kolmogorov - Smirnov test indicates that the five distributions can provide good fits for the diameter data, because their p-value of calculated D-values were greater than significance level (Sig. level) 0.05, except plot 13 (in rich forest) and plot 20 (in extremely rich forest). This implies the null hypotheses were accepted for 18/20 distributions, meaning the data followed the specified distribution.

The distribution of diameter was well described by the Log–normal function for 8/20 plots, and by Beta, Weibull 2P, Gamma function for 2/20, 0/20, 5/20, respectively. However, three – parameter Weibull distribution was more flexible in fitting the diameter data when tested with Kolmogorov - Smirnov because it has the highest p-value of calculated D-values for 18/20 plots.

A number of different distribution functions have been used to model diameter distributions, including Beta (Zohrer 1972; Li *et al*., 2002), two – parameter Weibull (Bailey and Dell, 1973; Rennolls *et al*., 1985), three – parameter Weibull, and Lognormal (Bliss and Reinker, 1964).

The Weibull distribution, introduced by Bailey and Dell (1973) as a model for diameter distributions, has been applied extensively in forestry due to (1) its ability to describe a wide range of unimodal distributions including reversed-J shaped, exponential, and normal frequency distributions, (2) the relative simplicity of parameter estimation, and (3) its closed cumulative density functional form (Bailey, Dell, 1973; Schreuder, Swank, 1974; Schreuder *et al*., 1979; Little, 1983; Rennolls *et al*., 1985; Mabvurira *et al*., 2002), and (4) its previous success in describing diameter frequency distributions within tropical rainforests (Le Sau, 1996; Dao Cong Khanh, 1996; Pham Quy Van, 2018; Cao Thi Thu Hien and Nguyen Hong Hai, 2018; Nguyen Quang Phuc, 2019).

Weibull distribution also was adjudged

more flexible in a research carried out in Gorazbon district of Kheyroudkenar forest by Namiranian (1990) and Mataji *et al*., (2000). Both scientists, using Kolmogorov-Smirnov tests showed that Weibull distribution could determine diameter distribution of trees.

Table 4 shows the parameter values of the selected distribution functions.

Table 4. Parameter estimates of Lognormal and Weibull 3P distributions for tropical rainforests in 18 plots

Forest state	Plot	Distribution	Parameters μ	Parameters δ	Parameters β	Parameters α	D	p-value	Sig. level
Poor forest	1	Lognormal	2.804	0.487			0.074	0.320	0.05
	2	Weibull 3P	5.891		1.571	9.889	0.042	0.697	0.05
	3	Weibull 3P	6.885		1.281	6.921	0.061	0.369	0.05
	4	Weibull 3P	5.912		1.417	10.157	0.122	0.114	0.05
	5	Weibull 3P	9.983		1.606	8.372	0.100	0.253	0.05
Medium forest	6	Weibull 3P	5.986		1.061	10.336	0.060	0.062	0.05
	7	Lognormal	2.891	0.440			0.088	0.100	0.05
	8	Lognormal	2.842	0.451			0.072	0.305	0.05
	9	Weibull 3P	6.213		1.067	10.450	0.081	0.200	0.05
	10	Lognormal	2.878	0.512			0.069	0.257	0.05
Rich forest	11	Weibull 3P	5.715		1.066	10.511	0.073	0.064	0.05
	12	Weibull 3P	5.697		1.289	12.550	0.085	0.400	0.05
	14	Weibull 3P	6.008		1.006	9.997	0.046	0.052	0.05
	15	Weibull 3P	5.946		1.029	10.956	0.048	0.061	0.05
Extremely rich forest	16	Weibull 3P	10.065		1.058	13.755	0.037	0.507	0.05
	17	Weibull 3P	10.120		1.089	15.152	0.034	0.500	0.05
	18	Weibull 3P	10.130		1.090	15.234	0.035	0.600	0.05
	19	Weibull 3P	10.155		1.070	12.597	0.047	0.162	0.05

The graphs of observed and estimated dbh class of the distribution functions show that there is no significant difference between the observed and predicted diameter frequencies (Figure 1). Some sample plots as according to the three – parameter Weibull distribution for observed frequency and estimated frequency was illustrated in Figure 1.

Figure 1 showed the distribution pattern of the dbh (m) of trees in tropical rainforests in Vietnam. The pattern shows that the majority of stems were concentrated in the first class or second class that is sufficient enough to replace trees in the upper dbh class in the future (i.e. when the big trees are harvested or when they die) (Aigbe and Omokhua, 2014) or another word, the type of decreasing distribution in tropical rainforests indicates that the regeneration is continuously happening as a consequence of the species' ability to adapt to environments (Ferreira *et al*., 2015). The implication of this is that the forests are still undergoing regeneration and recruitment, which are vital indicators of forest health and vigour (Jimoh *et al*., 2011). This is consistent with other reports for two other tropical rainforests (Boubli *et al*., 2004; Bobo *et al*., 2006). In addition, the poor and the medium forests were lacking large stems (over 60-cm DBH). Trees with a DBH greater than 70 cm were only found in the rich and extremely rich forests. This is similar to findings of Pham Quy Van (2018), Cao Thi Thu Hien and Nguyen Hong Hai (2018), Nguyen Quang Phuc (2019), Nguyen Thuy Hong (2019).

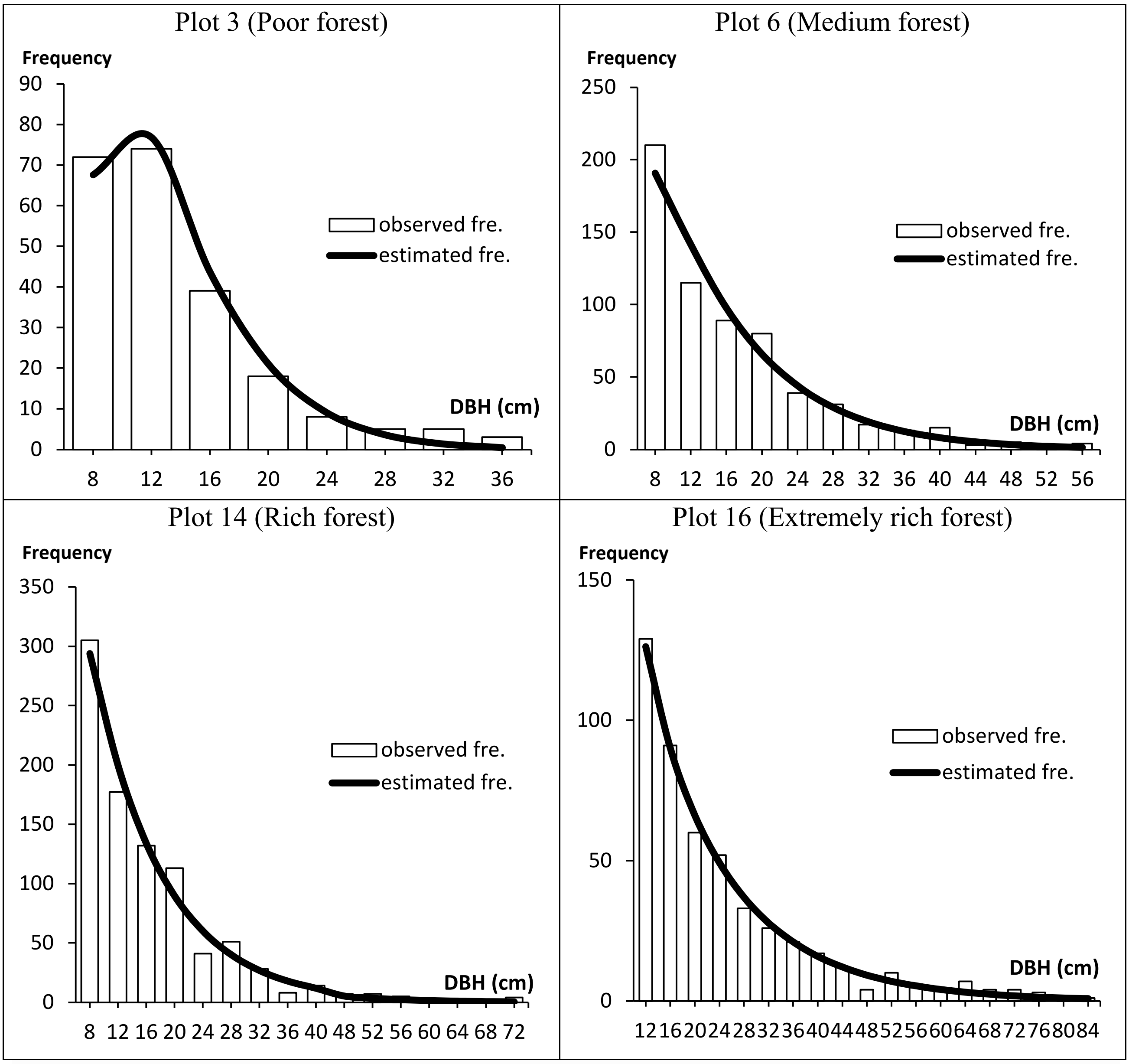

Figure 1. Diameter distributions and fitted curves of the models for several plots. Estimated frequency was from three – parameter Weibull distribution

The results of this study are also consistent with the results of many previous researches for the distribution of diameter at breast height in natural forest in Vietnam, such as the study in evergreen broadleaf natural forest in Kon Ha Nung (Le Sau, 1996), in Huong Son (Dao Cong Khanh, 1996), for natural forest state IIIA in An Lao district, Binh Dinh province (Pham Quy Van, 2018), Cao Thi Thu Hien and Nguyen Hong Hai (2018), Nguyen Quang Phuc (2019) also concluded that Weibull 3P distribution showed good flexibility to describe the diameter structure of the stand.

4. CONCLUSION

Tree diameter distributions play an important role in stand modelling. The area of rainforest in Vietnam showed diameter distributions with decreasing exponential curves and positive skewness. Using appropriate probability theories to predict trees distribution in tropical rainforest is important in estimation of productivity in different dbh class. In this study, probability distributions were applied to estimate the diameter distribution, and statistical methods were used to provide diameter distribution models.

Three – parameter Weibull function was the most flexible in fitting the diameter data in tropical rainforest in Vietnam when tested with Kolmogorov – Smirnov test, followed by Log–normal function. The Weibull 2P function did not depicted adequate development for frequency estimation of diameter class.

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MÔ PHỎNG PHÂN BỐ ĐƯỜNG KÍNH CỦA RỪNG MƯA NHIỆT ĐỚI Ở VIỆT NAM THEO NĂM HÀM XÁC SUẤT

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TÓM TẮT

Nghiên cứu này nhằm mô phỏng phân bố đường kính của rừng mưa nhiệt đới ở Việt Nam và lựa chọn phân bố phù hợp. Số liệu được thu thập từ 20 ô đo đếm, mỗi ô có diện tích 1 ha. Các hàm sau đây đã được thử nghiệm: Beta, Weibull (hai và ba tham số), Lognormal và Gamma. Các tham số của các hàm phân bố được ước tính bằng phương pháp tối đa hợp lý. Tiêu chuẩn Kolmogorov – Smirnov được sử dụng để lựa chọn hàm phân bố phù hợp nhất. Kết quả cho thấy phân bố đường kính của rừng mưa nhiệt đới được mô tả tốt nhất bằng phân bố ba tham số Weibull, tiếp theo là phân bố Long – normal, trong khi đó hàm Weibull 2P không thành công trong việc mô phỏng các phân bố này. Các tham số μ, β, và α của phân bố Weibull 3P lần lượt dao động trong khoảng 5,697 – 10,155; 1,029 – 1,606, and 6,921 – 15,234, trong khi đó các tham số μ và $\boldsymbol{\delta}$ của phân bố Log – normal lần lượt dao động trong khoảng 2,804 – 2,891 và 6,921 – 15,234. Phân bố đường kính có xu hướng số lượng cây giảm dần khi cỡ đường kính tăng lên.

Từ khóa: Cấu trúc đường kính, phân bố liên tục, rừng mưa nhiệt đới, tiêu chuẩn Kolmogorov–Smirnov, tối đa hợp lý.

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