Original Research Paper

Virtual Teak Tree Computational Model for Envisaging the Contribution by Using Functional-Structural Plant Modelling

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Abstract: The teak tree (*Tectona grandis*) has several positive contributions to the environment quality wood raw materials, deep and strong roots to help maintain soil stability and prevent erosion and habitat for various types of animals. On the other hand, teak also has an important role in producing oxygen and rarely do people directly see the growth of teak trees from small to large because it can take decades. This study aims to academically develop the Teak Tree Computational Model (TTCM) by using the method of Functional-Structural Plant Modeling (FSPM) and the growth Grammar-related Interactive Modelling Platform (GroIMP). FSPM and GroiIMP operated to morphologically construct the virtual Teak tree growth from trunk, branch and leaf to analyze its environmental and economic contribution. The dataset used in this research was 20 years of growth of the teak tree in Saradan, East Java, Indonesia. The model can simulate the morphological growth mechanism of single and multi-teak trees and can predict the contribution environmentally and economically. The model simulated that one 20-year-age teak tree can produce 17 L per hour of oxygen and Indonesian Rupiah (IDR) 1,200,000 of wood while in the real world teak tree can produce about 15 L per hour of oxygen and IDR 850,000-1,550,000.

Keywords: Plant Computational Modeling, Teak Tree, Functional-Structural Plant Modelling, Economical Contribution, Environmental Contribution

Introduction

The Teak tree (*Tectona grandis* with family *Verbenaceae*) is a tree species originating from Southeast Asia and growing in several countries in the region (Kusbach *et al*., 2021). Teak trees are known for their high-quality wood and are often used as raw materials for furniture and buildings. Teak tree wood is used for a variety of applications, such as furniture, construction and other products. Knowledge of teak tree morphology also helps in determining suitable applications and making efficient use of wood resources (Stewart *et al*., 2021). However, not everyone knows that Teak trees also have an important role in the environment, such as helping to maintain soil stability and maintaining air quality. Teak trees play an important role in shaping the forest ecosystem and contribute to global sustainability (Chayaporn *et al*., 2021).

The decades of growth of teak trees have resulted in many people never seeing the growth process of teak trees. They can grow to a height of 40-70 m and have a trunk diameter of up to 2 m and their leaves are oval with a pointed tip and long stems (Orwa *et al*., 2009). The teak tree has a distinctive shape with neatly arranged branches and alternate leaves. Teak tree trunks have a large diameter and are dark brown in color. The leaves of the teak tree are oval with a pointed tip and long stems. Teak tree leaves are dark green and large. The roots of the teak tree are fibrous and well-developed to help the tree maintain stability. The cambium layer of teak trees functions to form new layers of wood. Teak tree wood has a dark brown color and is smooth and hard in texture (Huy *et al*., 2022).

The modeling that will be used in this research is tree or Plant Computational Modelling (PCM). PCM is a computational method used to model the physiological, morphological and ecological processes of trees. It is a part of the research domain for environmental informatics and it is very fruitful to be adopted for environmental engineering efforts. Indeed, PCM combines several domains (biology, botany, environment, etc.,) to see one tree's response to environmental and other factors, such as climate, nutrition and pests. This model aims to understand the mechanisms of tree growth and development, as well as assist in predicting how trees will react to environmental changes (Jabar and Utama, 2021).

Several research conducted in the area of PCM like green amaranth, basil, Bok choy, etc. In short, from previous research, no one has yet visualized the growth of teak trees from trunk, branches and leaves and even calculated the economic and environmental contributions made by teak trees, making this research different from others.

Furthermore, little knowledge about the economy of Teak trees, the contribution of teak trees to the environment, especially as a producer of oxygen and the difficulty of seeing the growth of teak trees from small to large is the main objective of this research to make the virtual model of Teak tree which will show the mechanical growth or virtual growth of teak trees, economy and environment contribution. The fundamental method of Functional-Structural Plant Modelling (FSPM) executed in the growth Grammar-related Interactive Modelling Platform (GroIMP) is scientifically operated. This model combines biological and physical data to model the process of growth and development of teak trees. It aims to understand the mechanisms of growth and development of teak trees and assist in envisaging how the tree will respond to changes in the environment. Practically, it can be used as a green lab for virtually analyzing the tree's morphological growth and contribution. Conclusively, the article is constructed in five parts: Introduction, related works, research methodology, result and discussion and conclusion and further works.

Much research regarding the Teak tree model has been conducted already. Nölte *et al*. (2022) developed a model for predicting forest growth in Costa Rica and Panama. The prediction applied to a wide range of site conditions and management strategies for four native tree species (i.e., *Dipteryx oleifera*, *Dalbergia retusa*, *Hieronyma alchorneoides*, *Vochysia guatemalensis*) and teak tree.

Additionally, Huy *et al*. (2022) modeled the teak tree stand growth in tropical highland areas. A simultaneous model was constructed to predict the growth of the planted teak stand and the planted growth and yield of teak were predicted under varying management regimes.

Furthermore, Chi *et al*. (2022) constructed a 3D digitized model to model a leave arrangement (phyllotaxy) in a plant, specifically for mangrove species. The model can simulate the light interception by particularized leaves. The constructed model can measure and visualize the photosynthetic contributions of plants.

Then, Fabrika *et al*. (2019) developed a model of structural growth of Norway's young spruce trees in a highly dense naturally regenerated forest stand specifically in branching strategy. Jabar and Utama (2021) created a model combining PCM with the Decision Support Model (DSM). The PCM was constructed based on the Green Amaranth plant supplying information on plant mechanical growth and then the DSM was made to suggest the agricultural investment decision. Also, Utama and Wibowo (2022); Utama and Gunawan (2023) conducted research on 3D visualization growth for respectively Bok Choy and Merkus Pine tree and PCM to aid in investment decisions and economic contribution measurement. For this research, PCM was used with the FSPM method to visualize the growth of teak trees and measure the contribution of teak trees like investment and oxygen production.

Materials and Methods

Four main stages are conducted in this research. It is represented in Fig. 1. Situational object analysis is the first stage of the research. Method of deep literature Four main stages conducted in this research to achieve the research objectives consist of: (1) Situational object analysis, (2) Data collection, (3) Computational model development and (4) Model validation. It is represented in Fig. 1 using a UML activity diagram (Dennis *et al*., 2015).

Situational Object Analysis

Situational object analysis is the first stage of research. The in-depth literature review method was operated to obtain a deeper understanding of the research subject and explore various theoretical bases related to the research. A comprehensive review of existing literature regarding teak trees, their contribution to the environment and their economic value was carried out to understand current knowledge and identify gaps in the literature. The review was carried out by searching relevant academic journals, books and online library sources (e.g., science direct). This is done to provide new contributions to research and prevent duplication or plagiarism with existing research.

Data Collection

Data collection is the second stage. The method of literature study also functioned for the stage by searching for papers containing teak tree data. Data related to teak tree growth and their environmental impact were collected from various sources, such as stem growth and diameter of Teak trees up to 20 years (Ginoga *et al*., 2005), leaf length and width (Sumiati, 2021), calculation of the amount of oxygen based on the number of leaves (Rusmayadi *et al*., 2023) and class of teak wood based on stem tip diameter (Abdulah *et al*., 2021). The data are carefully selected to ensure that it is relevant and of high quality.

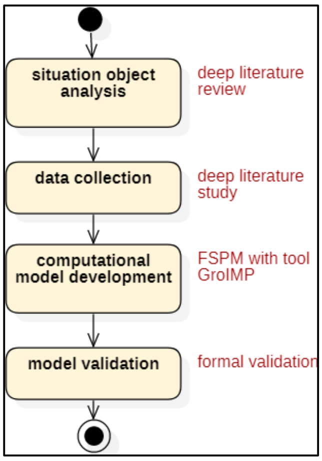

Fig. 1: Research stages with methods

Computational Model Development

The third stage involves the creation of a computational model. Using GroIMP and the object-oriented eXtended L-System (XL) programming language, a computational model of Teak trees and their contribution to the environment was developed based on the data collected and the FSPM method (Zhang *et al*. 2021). The teak tree computational model was rendered in 3D using GroIMP's Relational Growth Grammar (RGG) concept (Kniemeyer *et al*., 2007). The results of this model will provide information from the calculation growth rate and size of the teak tree's stem and leaves in each year of its life. Based on this growth rate data, the model can also calculate oxygen production and the economic contribution of wood.

Model Validation

The model validation stage is the final stage. The developed computational model was validated using real-world data to ensure that it accurately represents the mechanical growth of teak trees, as well as their environmental and economic contributions. This is accomplished by comparing the model's output data with real-world observation data of teak trees using a formal validation method (Hartanto and Utama, 2020) to determine the degree of truth in the resulting model. The final model validation value is calculated here and a value of 1.00 indicates that the model constructed is both academically and practically correct.

Results and Discussion

The Constructed Teak Tree Model

The algorithm of the constructed model is described by an activity diagram; it is clearly presented in Fig. 2. The model activity begins with setting the input of parameters. The first parameter is the Teak tree's growth year (activity growth year), which is 20 years. The growth year value is freely defined, depending on the age that is going to be analyzed. The growth activity is executed up to 20 times, depending on the growth year determined previously. The next parameters are the tree organ's initial value such as trunk height, trunk diameter, leaf height, and leaf width, where these parameters will be defined first before teak tree growth. The next step is to determine the min-max value for each tree organ so that teak trees can grow dynamically every year randomly. Parameters value and min-max value were defined based on a dataset from (Ginoga *et al*., 2005; Sumiati, 2021).

Then, the model computes all tree organ's data (e.g., the number of leaves, tree trunk diameter, tree height, length and width of the whole leaf) via the activity calculate all tree organs each year. The model can also determine the volume of tree trunks and the area of all leaves in the activity and calculate the area and volume of tree organs. Following the calculation, the model displays the outcomes of computing this data each year. When the teak tree reaches the age of 20 years or the growing activity is conducted 20 times, the model calculates and displays the amount of oxygen generated as well as the economic selling price of one teak tree wood.

Virtual Teak Tree

In terms of the morphological model of the single above-ground Teak tree at the age of 20 years, a toy model without texture is shown in Fig. 3 and a toy model with texture is shown in Fig. 4. Each model is made of three parts such as trunk, branch and leaves. The tree root itself is not considered academically in the model. All the above-ground tree organs are computed in GroIMP using basic statistical and mathematical concepts for yearly growth.

Some parts of the virtual plant model are described in detail here (e.g., development stage, leaf number, vegetative development, leaf blade length, leaf blade width, trunk diameter, trunk and leaf texture, etc.). However, there are still many parts not deliberated in detail here (e.g., leaf angles, leaf azimuth, relationship between the main stem and branch, bending decision, etc.).

The increment value of the main stem diameter and height functions mathematically to depict stem growth and development, where the randomized increment value of the diameter is 0.092±0.02 dm and the randomized increment value of the height is 8.05±2.95 dm. Each Teak tree branch has 5% of the diameter of the main stem and begins to emerge in the fourth year. The number of leaves is also calculated in this model which is presented in Fig. 5 and if it was formulated exponentially, the formula can be seen in equation (1); where LN_t represents a t^{th} year leaf number and t donate t th year. For each leaf, the randomized increment length and width values are 4.4±3.1 and 2.95±1.95 dm respectively.

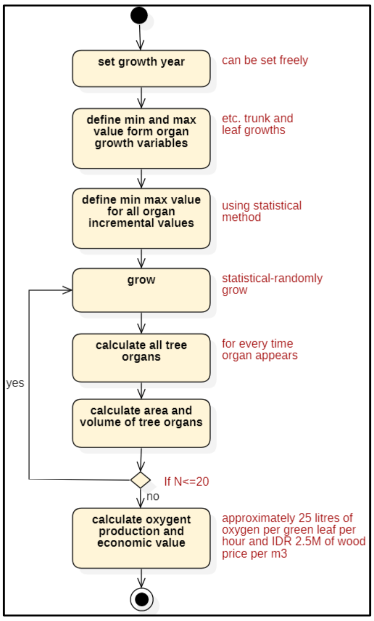

Fig. 2: The algorithm for the constructed model

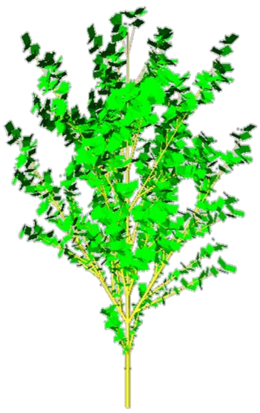

Fig. 3: Virtual model without texture of single above-ground teak tree

Fig. 4: Virtual model with texture of single above-ground teak tree

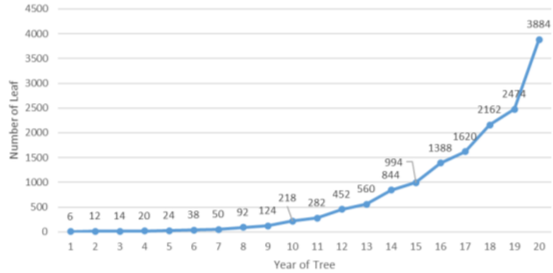

Fig. 5: Total leaf number in every year

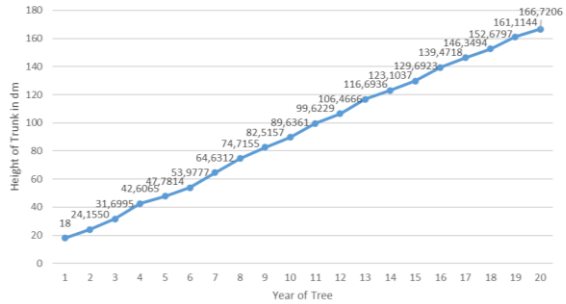

Fig. 6: The average trunk height in every year

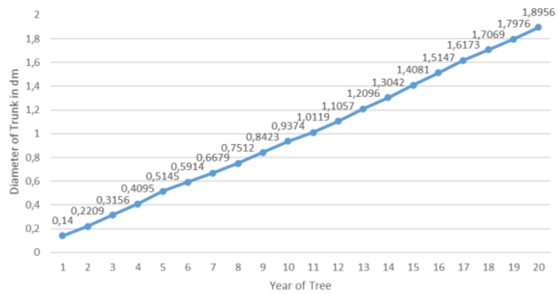

Fig. 7: Average trunk diameter in every year

Figures 6-7 show the yearly increase in height and diameter of a tree trunk respectively, while Fig. 8 exhibits the average length and width yearly of each leaf. The height trend for tree trunks is linearly exhibited via Eq. (2), where THt indicates a t^{th} year trunk height (in dm). The diameter of the tree trunk itself is linearly expressed via Eq. (3); where TD_t designates a tth-year trunk diameter (in dm). Also, average leaf width and length can be generally formulated by Eqs. (4-5) correspondingly; where LW_t defines a tth ear leaf width (in dm) and where LL_t indicates a t^{th} year leaf length (in dm):

$$LN_t = 5.448e^{0.3408t} \tag{1}$$

$$TH_t = 8.0514t{+}9.0415 \tag{2}$$

$$TD_t = 0.0923t{+}0.0295 \tag{3}$$

$$LW_t = 0.0910t{+}0.7991 \tag{4}$$

$$LL_t = 0.1472t{+}0.9689 \tag{5}$$

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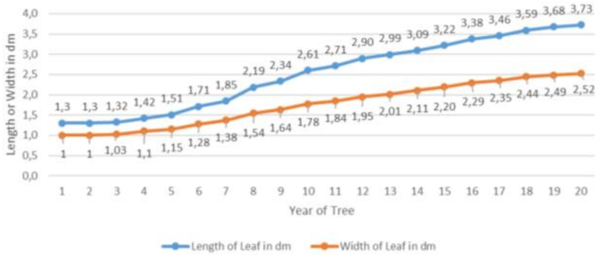

Fig. 8: Average leaf width and length

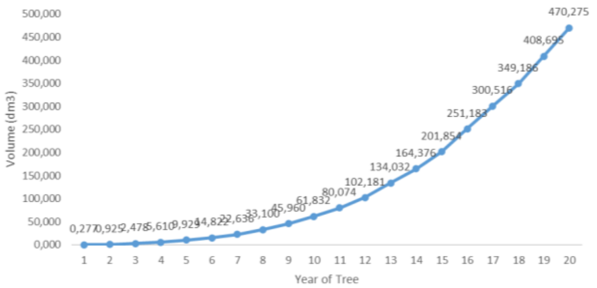

Fig. 9: Average trunk volume in every year

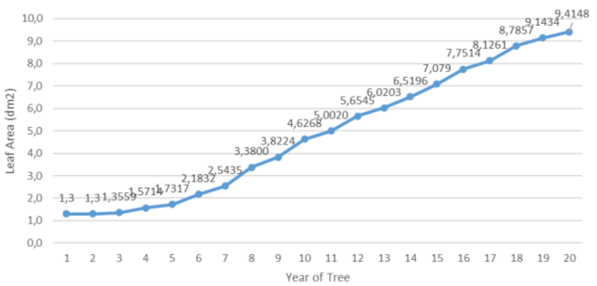

Fig. 10: Average leaf area per year

Fig. 11: The multi-tree model of 100 teak trees

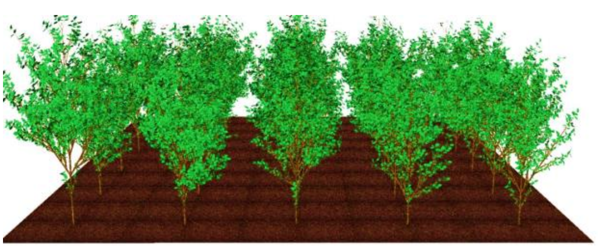

Fig. 12: The multi-tree model of 25 teak trees

In addition, the model can also determine stem volume and leaf area by using the calculation data for each part of the tree. The calculation of leaf area assumes that the leaf form is square. As a result, the formula for calculating the area of a leaf is the same as the formula for calculating the area of a square, which is the length of the leaf multiplied by the width of the leaf. For the stem volume for, the Eq. (6) operated to mathematically calculate the t^{th} year trunk volume (TV_t). Figure 9 exhibits the yearly volume expansion of tree trunks, whereas Fig. 10 displays the total leaf area each year. The trend of trunk volume in every year can be exponentially formulated via Eq. (7) and then the total leaf area in every year can be linearly expressed via Eq. (8); where LA_t is a t^{th} year leaf area:

$$TV_t = \pi \frac{TD_t^2}{4} . TH_t \quad (6)$$

$$TV_t = 23{,}246t - 111{,}09 \quad (7)$$

$$LA_t = 0.4822t - 0.1978 \quad (8)$$

Then, 1,000 teak trees may be planted in a 1-hectare area with a 3 m spacing. In this research, for visualization, we just developed a numerous teak tree model on an area of 25 teak trees spaced 3 m apart. The original textures of twenty-year-old teak tree trunks, branches and leaves were used to construct the model. Figure 11 shows a model of 100 teak trees planted in soil and Fig. 12 shows the multi-tree model for 25 teak trees.

Economic Value Simulation

The teak tree trunk model developed up to the age of 20 years has an average diameter of 11-19 cm and is classified as A1 Class teak. The economic value of selling teak tree trunks of class A1 is computed using the expected market value of IDR 2,500,000 per m^3 based on (Abdulah *et al.*, 2021). Fig. 13 shows the experimental results of several teak trees up to 1000 teak trees per hectare and the estimated profit. The experiments resulted in an average m^3 selling price of around IDR 1,200,000 per tree. When 10 teak trees are sold, it will give a profit of about IDR 11.000.000. This profit certainly does not really replace the hard work of workers in cutting and selling teak wood, so the profit will be felt more as the amount of teak wood sold increases. In this experiment it can be shown that the more teak trees planted, the greater the profit obtained.

Oxygen Production Simulation

Finally, the model can simulate the amount of oxygen generated by each teak tree. Generally, humans consume about 600 L of oxygen daily, or up to 25 L per hour. According to scientific estimates based on (Rusmayadi *et al.*, 2023), one leaf generates 5 mL of oxygen every hour.

Figure 14 shows a graph of the experimental results of several teak trees up to 1000 teak trees per hectare of land as well as the estimated oxygen produced per hour in liters. The experiment was created by running each tree model ten times and then calculating the average. The average amount of oxygen generated by one tree is roughly 17 L per hour, depending on the number of leaves produced. Figure 14, shows that planting 1000 trees can produce 14.444 L oxygen per hour, which means that in 1 h 1000 trees can provide oxygen for 24 persons in 1 day. In this experiment, the more trees planted, the more oxygen produced and more people are getting enough oxygen.

Model Verification and Validation

The verification and validation of the constructed model were done. The model has a verification value of 1.00. It means the model is verified or academically true. Several mathematical formulas are operated in the model. Two main model elements that have been verified are leaf area calculation, trunk volume calculation, economic value calculation and oxygen production calculation. The complete verification table can be seen in Table 1.

Table 1 shows the formula for leaf area and trunk volume calculation, Eq. (6) is used as a formula for calculating the trunk volume. The equation is a formula for officially calculating the cylinder volume that comes from Taufik *et al*. (2017). In GroIMP, the modeling platform used in the study, the formula coded as "float trunkVolume = 3.14 * (totalDiameter/2) * (totalDiameter/2) * allTrunkHeight;". Those formulas (between reference and model code) have the equivalent connotation; thus, the model element considered is academically true. The other one is a formula used to measure the leaf area. It is a rectangular area calculation (as the Teak leaf has a rectangular structure expectedly); where the area is width times length and the formula is coming from Syahbana (2014). The formula is coded in GroIMP as "float allLeafArea = widthAllLeaf * lengthAllLeaf;". Since both formulas in Table 1 have an identical sense. It indicates that the constructed model operates the right formula and gets the verification value 1.00 for such a model element of leaf area calculation obtained.

Moreover, the model also has a validation value of 1.00. It means, the data operated in the model are true, or in other words can be said that the model is practically valid. The summary of the validation for six model elements can be seen in Table 2. For example, models can produce the result of single leaf area calculation. On average, it is 3.38 dm^2 in the 8^{th} year (Fig. 10). Based on real data, the range of leaf area is in-between 19.025±17.725 dm^2 which are min-max value calculated from the dataset based on (Sumiati, 2021). It means if the value of the single leaf area is 9.41 dm^2 in between the min value of 1.3 dm^2 and max value of 36.75 dm^2 then the model is valid, with a validation value of 1.00.

Another example, the model shows that the Teak trunk volume in the 20^{th} year is 470.275dm^3 (Fig. 9). Based on real data, one single Teak tree can have a trunk volume in the middle of 516.286±350.253 dm^3 which are minimum value calculated from the dataset based on Ginoga *et al*. (2005). It says that the trunk volume value is between the min value of 166.033 dm^3 and the max value of 866.539 dm^3 which shows that the trunk volume calculated by the model is valid practically, the value is still in between the real value.

Table 1: Model verification result

Model elements	In reference	In model	Trueness	Verification value
Leaf area calculation	L = length × width	widthAllLeaf * lengthAllLeaf	V	1.00
Trunk volume calculation	$V = ¼ \times \pi \times d^2 \times t$ or $V = \pi r^2 \times t$	3.14 * (Totaldiameter/2) * (Totaldiameter/2) * allTrunkHeight	V	1.00
Verification value				1.00

Table 2: Model validation result

Model elements	Value in model	Value in real	Trueness	Validation on value
Leaf length in 20^{th} year	3.73 dm	4.400±3.1000 dm	V	1.00
Leaf width in 20^{th} year	2.52 dm	2.950±1.9500 dm	V	1.00
Leaf area in 20^{th} year	9.41 dm^2	19.025±17.725 dm^2	V	1.00
Trunk length in 20^{th} year	166.72 dm	161.000±59.000 dm	V	1.00
Trunk diameter in 20^{th} year	1.90 dm	1.840±0.40 dm	V	1.00
Trunk volume in 20^{th} year	470.28 dm^3	516.285±350.255 dm^3	V	1.00
Validation value				1.00

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Conclusion

This research succeeded in developing the virtual Teak tree predicting the amount of oxygen and economic value. At the age of 20, 1 teak tree can produce 17 L/h oxygen and sell around IDR 1,200,000 while 1000 teak trees can produce 14,000 L/h oxygen and sell around IDR 1,200,000,000. The FSPM-GroIMP method is used to construct the model being able to visually simulate a morphological Teak tree growth per year for 20 years. The visualization contains the calculations of total leaf, trunk diameter, trunk height, trunk volume, length of total leaf, width of total leaf and leaf area per year. The model itself has verification and validation values of 1.00 which can be seen in Tables 1-2, which means the model successfully makes virtual growth of the teak tree and it is academically and practically true.

This research could aid the Teak entrepreneur in predicting the economic value of teak trees and aid nature organizations in predicting the amount of oxygen produced by teak trees. The model produced also can help the agronomist, forest and environment researcher in seeing the morphological teak tree growth in an easy-academic-manipulated computer model ecosystem.

Suggestions for future research to see all teak tree organs' behavior in more detail and try to correlate them to other ecological issues, such as the effect of rainfall, temperature, planting location and weather. All of this can be done by gathering data on other teak trees' organ growth, learning more deeply about research on ecological issues and more in-depth use of GroIMP-FSPM. Furthermore, dataset construction can be expanded to include more than 20 years and in a deeper time range (e.g., per month).

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Author's Contributions

Bryan Aleron and Indra Gunawan: Collect and analyze data, construct, simulate and finalize the model. Also drafted and finalized the manuscript.

Ditdit Nugeraha Utama: Wrote and finalized the manuscript.

Ethics

This manuscript represents the authors' original work and has not been previously published elsewhere. The authors have diligently reviewed and approved the content of this manuscript, ensuring its accuracy and adherence to academic standards. The research and publication process has been conducted with a commitment to research integrity and ethical practices. No potential ethical issues or conflicts of interest have arisen during this study. We have adhered to the ethical guidelines outlined by BINUS University to ensure the ethical conduct of this research. We are dedicated to upholding the highest standards of research ethics and any concerns or inquiries regarding the ethical aspects of this manuscript can be directed to the corresponding author.

References

Abdulah, L., Imanuddin, R., & Utama, A. P. (2021, July). The teak log volume estimation model for Sawn Timber: Case in Forest Management Unit (FMU) Bojonegoro-Perhutani-East Java-Indonesia. In *IOP Conference Series: Earth and Environmental Science* (Vol. *819*, No. 1, p. 012081). IOP Publishing. https://doi.org/10.1088/1755-1315/819/1/012081

Chayaporn, P., Sasaki, N., Venkatappa, M., & Abe, I. (2021). Assessment of the overall carbon storage in a teak plantation in Kanchanaburi province, Thailand-Implications for carbon-based incentives. *Cleaner Environmental Systems*, *2*, 100023. https://doi.org/10.1016/j.cesys.2021.100023

Chi, F., Streit, K., Tavkhelidze, A., & Kurth, W. (2022). Reconstruction of phyllotaxis at the example of digitized red mangrove (*Rhizophora mangle*) and application to light interception simulation. *In silico Plants*, *4*(1), diac002. https://doi.org/10.1093/insilicoplants/diac002

Dennis, A., Wixom, B., & Tegarden, D. (2015). *Systems analysis and design: An Object-Oriented approach with UML*. John wiley and sons. ISBN-10: 1118804678.

Fabrika, M., Scheer, Ľ., Sedmák, R., Kurth, W., & Schön, M. (2019). Crown architecture and structural development of young Norway spruce trees (*Picea abies Karst*.): A basis for more realistic growth modelling. *BioResources*, *14*(1), 908-921. https://doi.org/10.15376/biores.14.1.908-921

Ginoga, K. L., Wulan, Y. C. and Djaenudin, D. (2005). Carbon and its role in increasing the business feasibility of teak (*Tectona grandis*) plantations in KPH Saradan, *East Java. Journal of Forestry Social and Economic Research*, *2*(2), pp. 149-167. https://doi.org/10.20886/jpsek.2005.2.2.149-167

Hartanto, M., & Utama, D. N. (2020). Intelligent decision support model for recommending restaurant. *Cogent Engineering*, *7*(1), 1763888. https://doi.org/10.1080/23311916.2020.1763888

Huy, B., Truong, N. Q., Khiem, N. Q., Poudel, K. P., & Temesgen, H. (2022). Stand growth modeling system for planted teak (*Tectona grandis* Lf) in tropical highlands. *Trees, Forests and People*, *9*, 100308. https://doi.org/10.1016/j.tfp.2022.100308

Jabar, B. A., Utama, D. N., & Rachmawati, I. D. A. (2021). Plant computational modelling of Green Amaranth for Predicting Economic Investment. *ICIC Letters Part B: Applications*, *11*(9). https://doi.org/10.3844/jcssp.2022.715.723

Kniemeyer, O., Buck-Sorlin, G., & Kurth, W. (2007). GroIMP as a platform for functional-structural modelling of plants. *Frontis*, 43-52. https://doi.org/10.1007/1-4020-6034-3_4

Kusbach, A., Šebesta, J., Meason, D. F., Mikita, T., Meyrat, A. M. C., Janata, P., ... & Smola, M. (2021). Site-specific approach to growth assessment and cultivation of teak (*Tectona grandis*) in Nicaraguan dry tropics. *Forest Ecology and Management*, *480*, 118658. https://doi.org/10.1016/j.foreco.2020.118658

Nölte, A., Yousefpour, R., Cifuentes-Jara, M., Piotto, D., Murillo, O., Zúñiga, P., & Hanewinkel, M. (2022). Broad-scale and long-term forest growth predictions and management for native, mixed species plantations and teak in Costa Rica and Panama. *Forest Ecology and Management*, *520*, 120386. https://doi.org/10.1016/j.foreco.2022.120386

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A. (2009). Psidium guajava. *Agroforestry Database: a Tree Reference and Selection Guide Version*, *4*. https://www.growables.org/information/TropicalFruit/GuavaAgroforestry.htm

Rusmayadi, G., Salawati, U., Susanti, H., Adriani, D. E., Hidayat, T., & Saidy, R. (2023). Change Climate and Its Impact on Rain Patterns in The Equatorial Region. Journal of Namibian Studies: History Politics Culture, 34, 197-213. https://doi.org/10.59670/jns.v34i.997

Stewart, H. T., Race, D. H., Rohadi, D., & Schmidt, D. M. (2021). Growth and profitability of smallholder sengon and teak plantations in the Pati district, Indonesia. *Forest Policy and Economics*, *130*, 102539. https://doi.org/10.1016/j.forpol.2021.102539

Sumiati, S. (2021). The Use of Ethanol and Acetone Solvents in the Working Procedure of Total Chlorophyll Extraction of Teak Leaves (*Tectona grandis*) with the Spectrophotometric Method. *Indonesian Journal of Laboratory*, *4*(1), 30. https://doi.org/10.22146/ijl.v4i1.65418

Syahbana, A. (2014). Alternative Understanding of the General Concept of the Area of a Flat Wake. *Edumatica: Journal of Mathematics Education*, *4*(02). https://doi.org/10.22437/edumatica.v4i02.2066

Taufik, T., Azwar, A., & Bukhari, B. (2017). Design a Sawdust Kneading Machine with Polymer resin Using an Electric Motor Drive. *Journal of Applied Science Machinery*, *1*(1), pp. 7-12. https://doi.org/10.33504/manutech.v8i01.76

Utama, D. N., & Wibowo, A. (2022, February). Virtual plant computational model of green-leaf vegetable plant bok choy (*Brassica chinensis* L.) for investment decision. *In IOP Conference Series: Earth and Environmental Science* (Vol. *998*, No. 1, p. 012049). IOP Publishing. https://doi.org/10.1088/1755-1315/998/1/012049

Utama, D. N., & Gunawan, I. (2023). An Object Driven Model of Above-Land Merkus Pine Tree for Quantifying the Commercial Contribution with Functional-Structural Plant Modelling. *IEEE Access*. https://doi.org/10.1109/ACCESS.2023.3338719

Zhang, Y., Henke, M., Buck-Sorlin, G. H., Li, Y., Xu, H., Liu, X., & Li, T. (2021). Estimating canopy leaf physiology of tomato plants grown in a solar greenhouse: Evidence from simulations of light and thermal microclimate using a Functional-Structural Plant Model. *Agricultural and Forest Meteorology*, *307*, 108494. https://doi.org/10.1016/j.agrformet.2021.108494