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The Bionomic Equilibrium Model for Balancing Forest Conservation and Economic Growth: Empirical Evidence from Indonesia

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Abstract: The objective of this study is to balance forest conservation with economic growth while accounting for the rate of deforestation. The methodology employed in this research utilizes a mathematical modeling approach, specifically adopting the logistic model to represent forest growth rates. In addition, numerical analysis is applied to illustrate the impact of economic activities on forest areas. The data used in the study consist of deforestation rates in Indonesia from 2000 to 2021. The findings indicate that the rate of economic activity in forested areas is directly proportional to the reduction in forest area. If the rate of deforestation due to economic activity approaches the forest growth rate, the likelihood of forest area reduction increases, and forest depletion will occur if the two rates become equal. To resolve the dilemma between forest conservation and economic growth, this study proposes a solution consisting of three key steps: (1) establishing a minimum forest area that is strictly protected from economic exploitation; (2) setting the ratio between forest growth rates and economic activity rates as a primary foundation for ensuring sustainable forest conservation and economic development; and (3) calculating environmental costs, such as reforestation, based on the proportional relationship between deforestation rates and forest growth rates.

Keywords: Deforestation, Environmental Cost, Economy, Forest, Growth Rate

INTRODUCTION

A forest is defined as land exceeding 0.5 hectares, with trees taller than 5 meters, and a canopy cover of more than 10 percent, or with trees capable of reaching these thresholds. In other words, a forest is determined by the presence of trees and the absence of significant alternative land uses (FAO, 2018). Forests cover nearly one-third of the Earth's land area and play a vital role in regulating hydrological processes and providing essential ecological functions and services, such as water supply, water purification, biodiversity conservation, and carbon sequestration (Clerici et al., 2019; Creed et al., 2016; Liu et al., 2021; Zhang & Wei, 2021).

Indonesia employs a specific definition of "forest" that may differ from those used in other parts of the world. Under Indonesia's 1999 Forestry Law, a forest is defined as an ecosystem unit within a landscape, dominated by tree communities found in nature. There are three types of forests: (1) primary forests; (2) secondary forests; and (3) plantation forests (KLHK, 2022). Additionally, forests are categorized into naturally regenerating forests (further classified into primary forests and other naturally regenerating forests) and plantation forests (further divided into plantation forests and other planted forests) (FAO, 2020).

Throughout history, humanity has transformed natural forests into agricultural land, residential areas, and managed forests (Kastner et al., 2011). Forests have undergone substantial management activities (e.g., deforestation, reforestation, afforestation, and land conversion) in response to agricultural intensification, urbanization, and the need to balance economic development with environmental protection (Hou et al., 2023).

Population growth has increased the demand for food, fuel, fiber, and other natural resources. Forest resources have rapidly diminished due to the expansion of cultivated areas and excessive commercial logging for fuel and construction materials, accelerating the rate of forest depletion (Hao et al., 2019). The environment is a key factor in economic development (Caravaggio, 2020). The global community faces numerous environmental challenges, and the state of the environment continues to deteriorate in various ways (Steffen et al., 2018). The growing intensity of human activities over the past few centuries has led to a significant decline in forest cover, particularly in tropical regions, due to deforestation and degradation (Lewis et al., 2015).

Forests are a major source of energy and income in tropical regions, and economic growth influences forest cover and energy use patterns (Woldemedhin et al., 2022). Forest cover, energy use, and economic growth are interconnected. For instance, the production of firewood and charcoal leads to forest degradation (Adkins et al., 2012), which affects agricultural production and increases energy supply (Iiyama et al., 2017). In many countries, energy consumption rises with population growth (Ahmed et al., 2017; Begum et al., 2015). In developing countries, forests serve as the primary source of household energy, while agriculture provides an alternative energy supply for rural communities (Adkins et al., 2012).

Deforestation refers to the permanent conversion of forested areas into non-forested areas as a result of human activities (KLHK, 2022). Deforestation remains a significant challenge in many parts of the world, particularly in developing regions where small-scale, fragmented agricultural production is increasing (Pelletier et al., 2020; Pendrill et al., 2019). It is considered the second largest source of anthropogenic greenhouse gas (Smith et al., 2015) and a primary driver of biodiversity loss (Maxwell et al., 2016; Tilman et al., 2017).

There are three direct causes of deforestation: agricultural expansion, timber extraction, and infrastructure development. Additionally, several underlying factors contribute to forest degradation, including demographic, economic, technological, policy and institutional, cultural, and other factors (Geist & Lambin, 2001). Economic activities have directly played a significant role in accelerating deforestation rates. For instance, rising prices for forest products can incentivize illegal logging by making it more profitable (Cropper & Griffiths, 1994). These energy supplies directly facilitate social and economic activities.

Indonesia is one of the tropical regions with extensive forest cover. Significant pressure on Indonesian forests has been identified through regular forest resource monitoring activities. The deforestation rate from 2019 to 2022 decreased by 75 percent to 115,000 hectares, the lowest rate since 1990. The deforestation rate between 1996 and 2000 was 3.51 million hectares, which declined to 1.09 million hectares between 2014 and 2015, and further to 470,000 hectares in 2018-2019. This reduction was primarily driven by an 82 percent decrease in forest and land fires. Additionally, approximately 3 million hectares of degraded land have been rehabilitated over the past decade (KLHK, 2022).

Several factors, including efforts to control forest fires, a permanent moratorium on primary forest and peatland, the development of weather modification techniques, rehabilitation and reforestation efforts, successful replication of ecosystem and eco-riparian rehabilitation, the expansion of urban green spaces, the demarcation of protected areas and High Carbon Stock Forest (HCSF) within concession areas, efforts to address habitat fragmentation, and the strengthening of law enforcement, have collectively contributed to a significant reduction in deforestation in Indonesia between 2019 and 2021 (KLHK, 2022).

Research linking deforestation to economic activity has been extensively conducted (DeFries et al., 2010; Giljum et al., 2022; Henders et al., 2015; Kastner et al., 2011, 2014; Pendrill et al., 2019). Giljum et al. (2022) found that one of the drivers of deforestation is industrial mining activity, particularly in tropical regions. Approximately 3,264 square kilometers of forest have been lost directly due to industrial mining, with 80 percent of this loss occurring in just four countries: Indonesia, Brazil, Ghana, and Suriname. Pendrill et al. (2019) explored agricultural expansion driven by foreign demand, examining the relationship between deforestation and international demand for agricultural commodities. Their findings suggest that around 29–39 percent of deforestation-related emissions are driven by international trade. While DeFries et al. (2010) investigated economic, agricultural, and demographic correlations in 41 tropical humid countries, concluding that rural population growth is not linked to forest loss, whereas urban and international demand for agricultural products is a key driver of deforestation. The aforementioned studies primarily focus on the impact of economic activity on forest area reduction but have yet to address the balance between deforestation and economic growth.

Unlike other studies, the novelty of this research lies in its approach to balancing forest conservation and economic growth while considering deforestation rates. In other words, this study aims to provide a new perspective on addressing the dilemma between forest preservation and economic development. The dilemma is twofold: (1) forests will continue to grow towards their maximum capacity if the rate of economic activity in forested areas decreases to a certain threshold; and (2) forests will continue to shrink, potentially approaching zero, if economic activity in forested areas significantly increases.

To address this dilemma, we employ a mathematical approach by adopting the logistic model (Bacaër, 2011; Brauer & Castillo-Chavez, 2012) to represent forest growth rates. The logistic model is more realistic compared to other models, such as the exponential model, in depicting forest growth. In the logistic model, in addition to incorporating the forest growth rate, a key assumption involves environmental carrying capacity, which represents the maximum limit for forest area expansion. This aligns with the reality that forest areas are spatially constrained. Additionally, we integrate an economic factor (Brauer & Castillo-Chavez, 2012; Seijo et al., 1998) into the logistic model to examine the influence of economic activities (such as mining, agriculture, housing, plantations, livestock farming, and others) on forest area reduction leading to deforestation. The data used in this study are deforestation rates in Indonesia from 2000 to 2021, with 14 data points published by the Indonesian Ministry of Environment and Forestry (KLHK, 2022).

METHODS

Based on the data published by the Ministry of Environment and Forestry (KLHK), deforestation rates in Indonesia have generally fluctuated from year to year. The data span the period 2000-2021, comprising 14 data points (see Figure 1). The deforestation rate from 2000 to 2001 showed a downward trend, but during the 2011-2015 period, the deforestation rate fluctuated. Subsequently, from 2015 to 2018, deforestation rates again showed a downward trend, though fluctuations occurred once more between 2018 and 2021. From 2000 to 2021, the highest deforestation rate was recorded during the 2014-2015 period at 0.82, while the lowest deforestation rate occurred during the 2019-2020 period at 0.07 (KLHK, 2022).

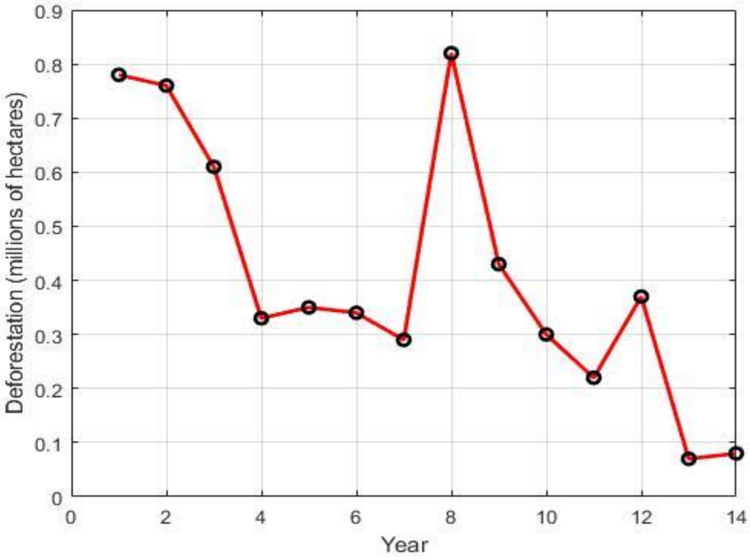


Figure 1. Deforestation Rate in Indonesia from 2000 to 2021

Source: Processed by the researcher, 2023

Logistic Model Approach

This study is quantitative research utilizing a mathematical modeling approach. The mathematical model adopted is the logistic model, which serves as a representation of forest growth. The logistic model applied in this context is as follows.

$$\frac{dF}{dt} = rF\left(1 - \frac{F}{K}\right), \tag{1}$$

where $r, K > 0$. The variable $F > 0$ represents the forest, the parameter r denotes the forest growth rate, and K is the maximum forest area (carrying capacity). Additionally, the operator $\frac{dF}{dt}$ is simplified to $\dot{F}$.

Equation (1) represents the natural growth of the forest without any external human activities affecting it. In reality, forest growth is influenced by human activities, particularly economic activities (denoted as D) (Woldemedhin et al., 2022). The fundamental assumption used in this model is that economic activities within forested areas result in deforestation (Geist & Lambin, 2001). Therefore, we assume that the rate of economic activity (qE) is directly proportional to the rate of deforestation (β).

By substituting the variable D into Equation (1), we obtain a new equation as follows:

$$\dot{F} = rF\left(1 - \frac{F}{K}\right) - D, \tag{2}$$

where $D = \beta F$, $\beta \approx qE$, with $q > 0$ and $E > 0$ representing, respectively, the forest harvest coefficient and the economic activity in forested areas. Generally, Equation (2) s known as the Bioeconomic Model.

Next, we calculate the net income (π) generated from economic activities leading to deforestation. The net income is given by the following equation:

$$\pi = (sqF - c)E, \tag{3}$$

Where $s > 0$ and $c > 0$ represent, respectively, the selling price per unit and the harvesting cost per unit of economic activity (Gordon, 1991; Schaefer, 1954).

To determine the value of β, we performed curve fitting on the annual deforestation rate data in Indonesia using Matlab software. After fitting, we calculated and analyzed the bionomic equilibrium from Equations (2) and (3). The final step of this study involves conducting numerical analysis using Matlab. The purpose of this numerical analysis is to explore the relationship between forests, the economy, and deforestation. This analysis is conducted by varying the parameters r and β.

RESULTS AND DISCUSSION

Determination of the Deforestation Rate Function

There are several methods to determine a function from a dataset, but in this study, we used curve fitting with Matlab. The goal is to approximate the data with a function.

With this function, predictions can be made about the deforestation rate for the following year.

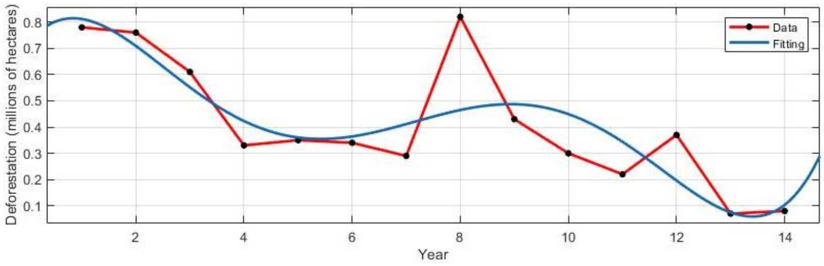
In this research, we approximated the data using three types of functions: polynomial, trigonometric, and rational. This approach was taken to find the best approximation function that could represent the data behavior with the least error. The curve fitting results for the three functions are presented in Table 1 and Figure 2.

Table 1. Curve Fitting Results of the Deforestation Rate Data for 2000-2021

No.	Function	SSE	*R-square*	*Adjusted R-square*	RMSE
1	$\beta(t) = 9.47x10^{-5}t^5 - 3.384t^4 + 0.04165t^3 - 0.2t^2 + 0.257t + 0.72$	0.229	0.703	0.518	0.169
2	$\beta(t) = 3.332\sin(0.0096t + 2.943) + 0.159\sin(0.8t + 0.734)$	0.209	0.729	0.559	0.162
3	$\beta(t) = \dfrac{27.82t^2 - 405.3t + 1498}{x^4 - 14.24t^3 + 86.6t^2 - 363.4t + 1679}$	0.071	0.908	0.828	0.101

Based on Table 1, it can be observed that the residual sum of squares (SSE) of 0.071 and the Root Mean Square Error (RMSE) of 0.101 for the rational function are smaller than those of the other functions. Additionally, the R-Square value of 0.908 and the Adjusted R-Square value of 0.828 for the rational function are higher than those of the other functions. Among the three functions analyzed, the rational function exhibits the smallest error. Therefore, the rational function is the best representation of the deforestation rate data, with the variable t representing time (see Figure 2).

(a)



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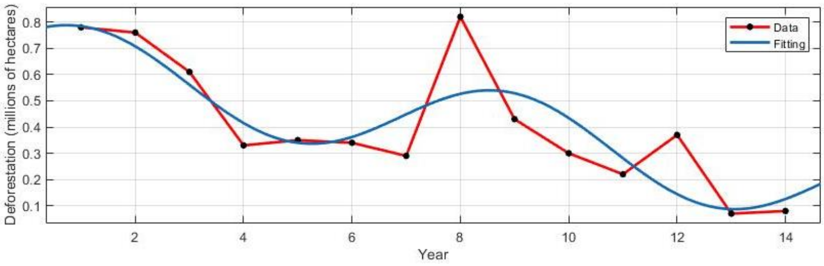

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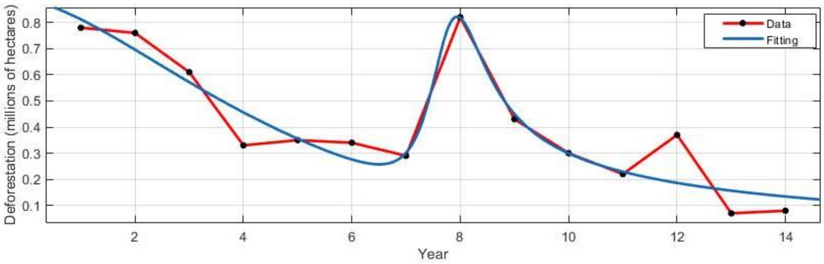

Figure 2. (a) Polynomial Function Curve Fitting; (b) Sine Function Curve Fitting; and (c) Rational Function Curve Fitting

(Source: Processed by the author using Matlab)

Estimation of Deforestation Rate for the Periods 2021-2022 and 2022-2023

Based on the previous fitting results, the function $\beta(t) = \frac{27.82t^2-405.3t+1498}{t^4-14.24t^3+86.6t^2-363.4t+1679}$ was found to have better accuracy compared to the other two functions. Using this function, we can estimate the deforestation rate for the periods 2021-2022 and 2022-2023. The deforestation rates for these two periods are shown in Table 2.

Table 2. Estimated Deforestation Rate for the Periods 2021-2022 and 2022-2023

No.	Period	Deforestation Rate (*millions of hectares*)
1	2021-2022	0.0918
2	2022-2023	0.0845

Table 2 shows that the deforestation rate for the period 2021-2022 is 0.0918, and for the period 2022-2023, it is 0.0845. These rates are higher compared to the deforestation rate for the period 2020-2021, which was 0.08.

Bionomic Equilibrium

In this section, we will analyze the bionomic equilibrium of Equations (2) and (3). To obtain the equilibrium point for both equations, we set $\dot{F}$ in Equation (2) and π in Equation (3) to 0 (zero). Thus, we get:

$$0 = rF\left(1-\frac{F}{K}\right) - qEF, \text{ and} \tag{4}$$

$$0 = (sqF - c)E. \tag{5}$$

By applying algebraic manipulation, the bionomic equilibrium points of Equations (4) and (5), are obtained as follows: $(F^*, E^*) = \left(\frac{K(r-qE^*)}{r}, \frac{r(sqK-c)}{sq^2K}\right)$. From this result, we can write $F^* = \frac{K(r-qE^*)}{r}$. This shows that forests will always exist if $r - qE^* > 0$, and the forest area fully depends on the forest growth rate r. Conversely, forests will disappear if $r = qE^*$. Additionally, we obtain $E^* = \frac{r(sqK-c)}{sq^2K}$. This implies that economic activity will continue if $sqK - c > 0$ and will cease if $sqK = c$.

Numerical Simulation

As mentioned earlier, the fundamental assumption of this study is that economic activities in forest areas contribute to deforestation. Thus, we assume that the rate of economic activity (qE) is directly proportional to the deforestation rate (β). In other words, the higher the rate of economic activity, the higher the deforestation rate, and vice versa. Furthermore, without generalizing too much in the calculations, we used the deforestation rate for the 2021-2022 period as the basis for analyzing the relationship between forests and the economy (see Table 2).

Next, the numerical simulation is divided into two cases: first, the change in F^* due to variations in the parameter r with the parameter β constant; and second, the change in F^* due to variations in the parameter β with the parameter r constant.

Case I Simulation

Based on previous calculations, the parameter value $\beta = 0.0918$ million hectares. We assume that $q = 0.2$ units, and $E^* = 0.459$ units, and K representing the forest area in 2021, is 95.6 million hectares. Since $\beta = 0.0918$, we obtain the following equation:

$$F^* = \frac{95.6(r - 0.0918)}{r}, r \geq 0.0918. \tag{6}$$

From Equation (6), the value of F^* depends solely on the parameter r. If the value of r varies, then the value of F^* will also vary. The following table shows the numerical results for various values of r.

Table 3. Bionomic Equilibrium with Variation in Parameter r

No.	Value F^*	r	β	q	E^*	r/qE^*	(F^*, E^*)
1	0	0.0918	0.0918	0.20	0.459	1	(0, 0.459)
2	60.7466	0.25				2.723	(60.7466, 0.459)
3	76.0976	0.45				4.902	(76.0976, 0.459)
4	80.9732	0.60				6.536	(80.9732, 0.459)
5	83.0627	0.70				7.625	(83.0627, 0.459)

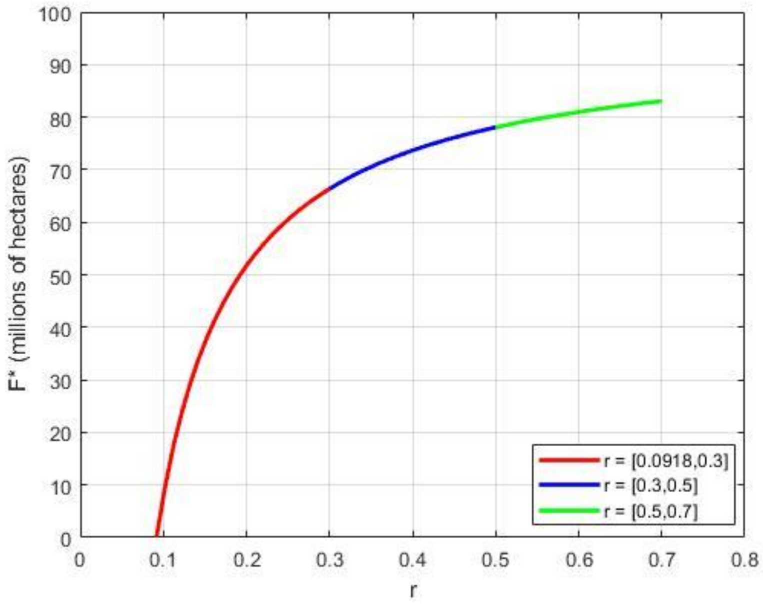

Figure 3. Relationship between F^* and r, with β Constant

(Source: Processed by the author using Matlab application)

Case II Simulation

In this section, we assume the value of the parameter $r = 0.7$. Given $r = 0.7$, we obtain

$$F^* = \frac{95.6(0.7 - \beta)}{0.7}, 0 \leq \beta \leq 0.7. \tag{7}$$

From Equation (7), the value of F^* depends on the value of the parameter β. If the value of the parameter β varies, then the value of F^* also varies. The table below presents the numerical results for various values of the parameter β.

Table 4. Bionomic Equilibrium with Variation in the Value of Parameter β

No.	Value F^*	r	β	q	E^*	r/qE^*	(F^*, E^*)
1	83.0627	0.70	0.0918	0.20	0.459	7.625	(83.0627, 0.459)
2	61.3479		0.25	0.25	1	2.800	(61.3479, 1)
3	34.1429		0.45	0.30	1.50	1.555	(34.1429, 1.50)
4	13.6571		0.60	0.35	1.714	1.166	(13.6571, 1.714)
5	0		0.70	0.40	1.75	1	(0, 1.75)

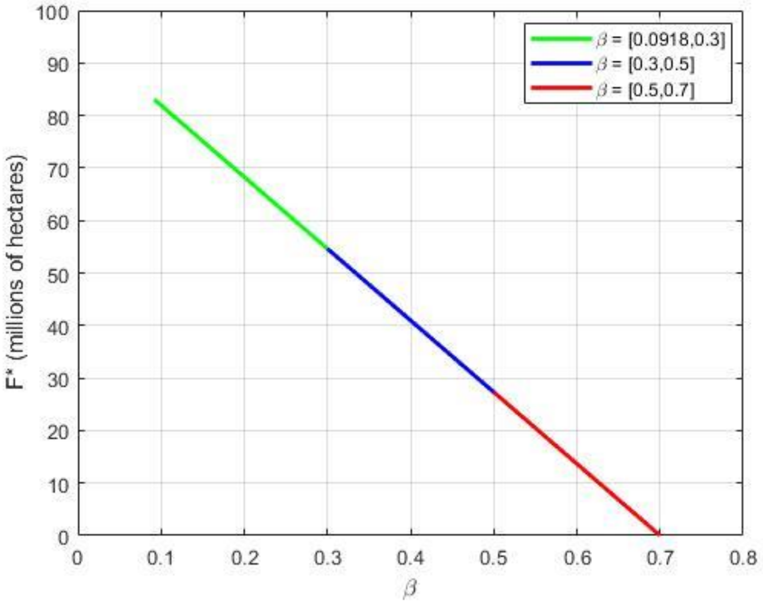

Figure 4. Relationship between F^* and β with r constant

(Source: processed by the author using Matlab)

Based on the results of Case I and Case II simulations, we formulated a scheme for the balance between forests and sustainable economic growth. This scheme is presented as shown in Figure 5.

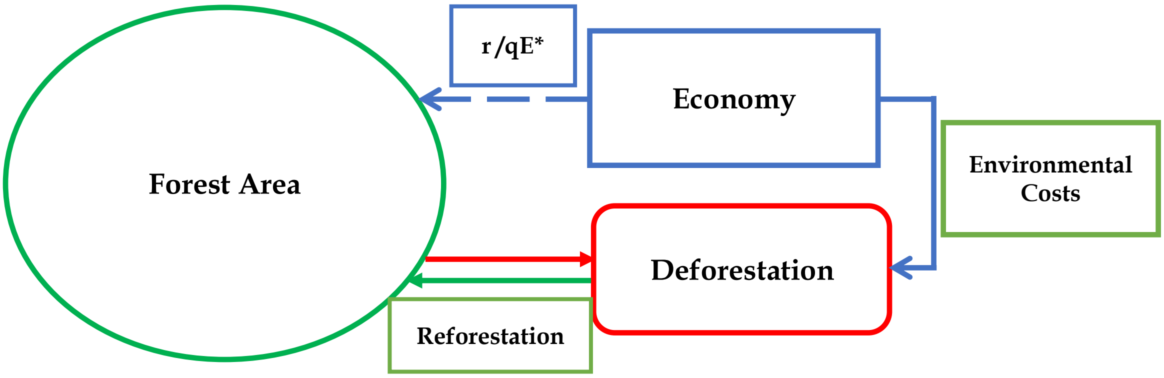

Figure 5. Scheme for the Balance between Forests and Sustainable Economic Growth

In summary, the interpretation of the balance scheme between forests and economic growth presented in Figure 5 indicates that economic activities affect the condition of forest areas through various forms of activities with a proportion of r/qE*, thereby resulting in deforestation. These economic activities generate profits. Subsequently, the total environmental costs are derived from the profits of these economic activities, which are then allocated to enhance forest growth (reforestation). In this scheme, the rate of reforestation must be greater than or equal to the rate of deforestation.

Estimation of Deforestation Rate and Bionomic Equilibrium Points

Based on the estimation results for the periods 2021-2022 and 2022-2023, the deforestation rate in both periods has increased compared to the deforestation rate for the period 2020-2021 (see Table 2). This indicates that measures to address deforestation in Indonesia (both concrete actions and regulations) have not significantly improved. As a result, the likelihood of a decrease in forest area is expected to increase in the future.

On the other hand, the calculation of bionomic equilibrium points indicates that forests depend on the rate of economic activity in forested areas. The higher the economic activity in forest areas, the greater the reduction in forest area, and vice versa. Therefore, economic activity plays a crucial role in the reduction of forest area. If the rate of economic activity leading to deforestation approaches the rate of forest growth, the likelihood of a decrease in forest area becomes greater, and forests will be depleted or disappear if the values of both rates are equal. This claim can be numerically substantiated. By assuming that the rate of forest growth remains constant at 0.7 units, the forest area significantly declines for various values of economic activity rates approaching the rate of forest growth (see Table 4). This also indicates that F^* and β are inversely related in a linear relationship (see Figure 4). The findings of this study are consistent with several studies conducted by (DeFries et al., 2010; Giljum et al., 2022; Henders et al., 2015; Kastner et al., 2011, 2014; Pendrill et al., 2019). For instance, a study by (DeFries et al., 2010; Giljum et al., 2022; Henders et al., 2015; Kastner et al., 2011, 2014; Pendrill et al., 2019). They presented assessments across biomes to demonstrate where industrial mining expansion has caused the most deforestation from 2000 to 2019. They found that 3,264 square kilometers of forest were lost directly due to industrial mining, with 80 percent occurring in just four countries: Indonesia, Brazil, Ghana, and Suriname. Furthermore, by controlling for non-mining determinants of deforestation, they also discovered that mining indirectly contributed to forest loss in two-thirds of the studied countries.

Unlike economic activities, the rate of forest growth plays a crucial role in addressing deforestation. If the rate of forest growth exceeds the rate of economic activity that leads to deforestation, the chances of increasing forest area become greater. This claim can also be substantiated numerically. By assuming that the rate of economic activity remains constant at 0.0918 units, the forest area increases for various values of the forest growth rate that exceed the rate of economic activity (see Table 3). This also indicates that F^* and r are directly related in a nonlinear relationship (see Figure 3).

Sustainability of Forests and Economic Growth

Based on the above discussion, two important points can be drawn: (1) forests will continue to grow toward their maximum limit if the rate of economic activity in forested areas decreases to a certain threshold; and (2) forests will continue to diminish, potentially approaching zero, if economic activity in forested areas increases significantly. This raises the question: can the relationship between forests and the economy operate in a harmonious and sustainable manner?

To address this dilemma, we propose a solution based on the bionomic equilibrium analysis discussed earlier (see Figure 5). The first step is to establish the minimum area of forest that cannot be economically exploited. The second step involves acknowledging that the bionomic equilibrium analysis guarantees the continued existence of forests if $r - qE^* > 0$, with the forest area entirely dependent on the rate of forest growth r. Therefore, establishing a percentage ratio between the rate of forest growth r and the rate of economic activity qE^* becomes paramount as a foundational basis for preserving forest areas while allowing economic activities to continue over an extended duration. Naturally, this ratio must take into account the first step. The third step involves calculating environmental costs, such as reforestation activities, based on the proportion of deforestation rate and forest growth rate. The environmental costs in question encompass both direct and indirect impacts arising from economic activities. Moreover, environmental costs are allocated from the economic profits π generated. Consequently, if the balance between forests and the economy has been achieved, the rate of forest deforestation can be controlled. This finding aligns with research conducted by (Hao et al., 2019), which demonstrates that with sustainable economic growth, timber yield and afforestation area initially increase and subsequently decline after reaching an appropriate turning point. Additionally, their findings highlight the positive effects of China's efforts to achieve a more balanced growth trajectory, where forest resources are consumed less and actively protected.

CONCLUSIONS

The determination of the deforestation rate function, estimation of the deforestation rate, bionomic equilibrium analysis, and numerical simulations have been conducted. A higher level of economic activity in forested areas corresponds to a greater rate of reduction in forest area, and vice versa. If the rate of economic activity resulting in deforestation approaches the rate of forest growth, the likelihood of a decrease in forest area will increase significantly, leading to the potential extinction or loss of forests if both rates are equal. Additionally, the rate of forest growth plays a crucial role in addressing deforestation. If the rate of forest growth exceeds the rate of economic activity that leads to deforestation, the chances of increasing forest area will become greater.

To address the dilemma between forests and economic growth, this study proposes a series of solutions aimed at balancing both, consisting of three steps. The first step is to establish a minimum area of forest that cannot be economically exploited. The second step involves determining the proportional ratio between the rate of forest growth r and the rate of economic activity qE^* , which serves as a fundamental basis for maintaining sustainable forest and economic activities in forested areas. The final step requires calculating environmental costs (e.g., reforestation) based on the proportional values of the deforestation rate and the forest growth rate. Environmental costs should be allocated from the economic profits π generated.

Based on the findings above, this study recommends that the government incorporate a balanced proportional relationship between the rate of forest growth and the rate of economic growth, along with consideration of environmental costs as two critical factors in formulating policies related to forest management in Indonesia.

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