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Review Article

Modelling the Impact of Human Population and Its Associated Pressure on Forest Biomass and Forest-Dependent Wildlife Population

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Mathematical models have been widely used to explain the system originating from human-nature interaction, investigate the impacts of various components, and forecast system behaviour. This paper provides a profound reference to the current state of the art regarding the application of mathematical models to study the impact of human population and population pressure on forest biomass and forest-dependent wildlife. The review focused on two aspects, namely, model formulation and model analysis. In model formulation, the review revealed that socioeconomic status influences forest resource consumption patterns, thus, stratification of the human population based on economic status is a critical phenomenon in modelling human-nature interactions; however, this component has not been featured in the reviewed models. Regarding model analysis, in most of the reviewed work, single parameter approach was utilized to perform uncertainty quantification of the model parameter; this approach has been proven to be inadequate in measuring the uncertainty and sensitivity of the parameter. Thus, the use of correlation or variance based methods, which are multidimensional parameter space methods are of significant importance. Generally, despite the limitations of many assumptions in mathematical modelling, it is revealed that mathematical models demonstrate the ability to handle complex systems originating from interactions between humans and nature.

1. Introduction

Forests play a significant role in maintaining the ecological balance of the ecosphere [1]. Forest maintains microclimate and water cycle [2], prevents soil erosion, and sequesters carbon dioxide from the atmosphere [3], as well as the source of wood, energy, medicine, and fodder [4]. The World Bank estimates that about one billion people worldwide depend on the forest as a primary source of medicine [5]. Furthermore, forests provide habitat for 80%-90% of the terrestrial biodiversity [6]. The highest ratio of endemics per area of all biodiversity hotspots is found in the forests of the eastern arc of mountains in Tanzania and Kenya [7]; it occupies an area of 2000 km^2 and offer habitat to about 121 endemic vertebrate species [5].

Despite the significant roles of the forest, the resources are under threat due to unrelenting pressure from the human population and its associated activities [8]. Human population growth has been shown to be significant around the world [9] putting pressure on forest resources [10]. The need for food and settlement to accommodate the rapidly growing human population is the major cause of deforestation and the destruction of wildlife habitats [11]. The challenge is exacerbated by poverty in developing countries such as Tanzania where the livelihoods of people highly depend on land and forest resources [12]. In particular, Shadrack et al. [13] reported that 90% of the households in Tanzania depend on wood charcoal and firewood as their main sources of energy. It is fairly to say if nothing is done to reduce the dependence of forest resource, Tanzania forest land is at risk of disappearing. Similarly, *The State of the World's Forests 2020* (FOSO) shows that forest land covers about 31% of the total world's land [14]; nevertheless, between 2010 and 2015, the world experienced a loss of 3.3 million hectares of forest areas [15]. Furthermore, the estimate shows that 137 species are lost every single day due to deforestation [16]. This means threat to forests is also a threat to biodiversity hotspots.

According to Duncan [17], consumption of forest resources depends on social economic status, human lifestyles, and industrial and agricultural structures, as well as population (human and wildlife) levels. In Africa, social economic status is contemplated as the most significant indirect cause of deforestation [18]. A large proportion of African households depend on forest resources for their livelihoods [13], as well as agricultural practices are inefficient due to the lack of advanced technologies [18], thus, putting more pressure on forest lands. Bhardwaj [18] reported that economic growth affects deforestation into two possibilities, either positive or negative. This phenomenon is hypothesized under the *Immiserization Theory*. The theory postulates that poor people tend to extract more natural resources to meet their needs, leading to forest degradation [19]. The theory is supported by the findings from Raphael et al. [20] that assets poor households depend more on forest-generated income than their counterparts. Conversely, economic growth prevents deforestation through the creation of off-farm employment and empowerment of the society to develop better forest management strategies and create environmental awareness for forest conservation [20]. Globally, extreme poverty has rapidly declined, World Bank estimates show that the number of people who live on 1.90 USD or less a day worldwide has dropped from 1.9 billion in 1990 to 736 million in 2015 [21]. Yet, in Sub-Saharan Africa, the number of people living in extreme poverty is increasing rapidly. The forecast shows that by 2030, 9 in 10 extremely poor people will be living in Sub-Saharan Africa [21], meaning increasing threats to Sub-Saharan Africa forests. In Africa, particularly in Tanzania, the rate of poverty reduction does not match the rate of population growth, leading to an increase in the number of households living under absolute poverty [22]. The proportion of the poor by geographic domain in Tanzania shows that 84.4% of poor people live in rural areas while 15.7% live in urban areas [23]. According to Bhardwaj [18], unsustainable consumption of natural resources contributes to poverty, and consequently environmental degradation. Therefore, studying the impact of population growth on forest resources has multiplied positive effects on finding better ways to reduce poverty and manage environments.

Despite the challenges, forests remain a vital source of livelihood for people in developing countries [24]. Therefore, attempts to completely limit peoples' access and utilisation of forest resources are not possible. However, the management of forest resources to manage harvesting and utilisation is feasible. Different scholars ([5, 25–32] and references therein) have studied the impact of population growth and its associated pressure on forest biomass both theoretically and experimentally. These studies try to understand the interaction between human population and forest biomass. The main questions that were posed are as follows: how does the system that governs human-forest-wildlife species interaction behave over time? What are the key parameters that drive the system? How fast can forest resources recover naturally from destruction? What are the measures needed to conserve the resources? And Is the developed model reliable? This review advances knowledge of the use of theoretical approaches under dynamic system models to understand variables and relationships that form complexity in human-forest interactions and make predictions about the behaviour of the system formed. Knowing that it is not possible to include all articles in the review, we used the procedures proposed by Meline [33] to select which studies to be taken into consideration. Particularly, the articles had to meet the following requirements in order to be included: the paper has been published in the journal listed in the Web of Science and the paper used dynamical systems as well as consists at least two of the keywords.

The rest of the review is structured as follows: Section 2 presents a systematic review methodology used; while in Section 3, various mathematical models that meet the inclusion and exclusion criteria are presented and analysed. The discussion and conclusion of what has been drawn from the Section 3 are presented in Section 4.

2. Materials and Methods

Given the abundance of publications and research interest in this area, the preestablished inclusion and exclusion guidelines suggested by [33] were established to assist in selecting the papers for the review. An in-depth literature search was carried out in order to identify and compile the publications pertinent to this review. The criteria considered in this review were as follows: the article was published in a journal that is listed on the Web of Science; the dynamical models were employed as the mathematical tool, as well as, at least two of the keywords (mathematical modelling, dynamical system, forest biomass, forest-dependent wildlife, and population pressure) appeared in the title or abstract. To accomplish that, the "OR" and "AND" logical operators were used to search the articles in four different search engines, namely, Google Scholars, Web of Science, Scopus, and ScienceDirect. This comprehensive search turned up a gross list of about 101 papers of which 42 were irrelevant to the focus of this review, leaving 59 articles for the review. Furthermore, the relevant articles were stratified by looking at the state variables used in modelling process, whereby eight groups were formed (Table 1 and Figure 1). The models presented in Subsection 3.1 are representative of each established groups. At least one author of this review thoroughly reviewed each of the selected papers, a number of attributes related to model formulation and model analysis, which are the focus of this review were noted and discussed.

Table 1: Groups of relevant articles based on the state variables used in modelling process.

Group	State variables in the model
Group 1	Forest biomass, wildlife species, and population pressure
Group 2	Forest biomass, wildlife species, and industrialization
Group 3	Forest biomass, wildlife species, human population, population pressure, and mining activities
Group 4	Forest biomass, wildlife species, human population, and industrialization
Group 5	Forest biomass, wildlife species, human population, and population pressure
Group 6	Forest biomass, wildlife species, human population, and human activities
Group 7	Forest biomass, human population, population pressure, industrialization, and economic measures
Group 8	Forest biomass, concentration of pollutants, and environmental pollution concentration

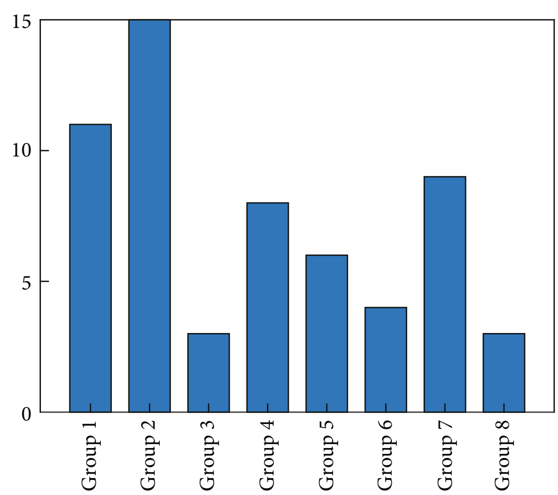

Figure 1: Number of relevant articles per group.

3. Mathematical Models

In the field of forest and wildlife management, mathematical modelling is not a new phenomenon. Management of natural resources such as forests involves many different interrelated variables. These variables and relationships that hold them together form systems that are complex in nature [34]. These complexities can be studied and analysed well by using theoretical models. Mathematical models, in particular the use of system of differential equations have been widely employed to investigate systems arising from human-nature interactions and provide predictable solutions [35]. Usually, these models use mathematical concepts to explain the system, study the effects of different components, and make predictions about the behaviour of the system [34].

3.1. Dynamical System Models. The dynamical system models are models used to define and predict the interactions between several compartments overtime of a phenomenon that is viewed as a system [35]. Mathematically, dynamical system can be described as

$$\dot{X} = \mathscr{G}(X, \theta, t), \tag{1}$$

such that

$$\begin{aligned} X &\in \mathbb{R}^n, \\ \theta &\in \mathbb{R}^m. \end{aligned} \tag{2}$$

Here, X is the set of state variables (compartments) while θ is the set of parameters which govern the links between compartments over time t.

Several researchers employed dynamical system models to study the dynamics of human-forest interaction (e.g., [26, 36–41]). This may be explained by the fact that, when human population and its associated pressure increases, the interaction between human population and forest biomass forms a complex system [3]. To address this challenge, researchers often use the system of differential equations to explain the system, study the effects of each different variable in the system and make predictions about the behaviour of the system [42].

Bahadur et al. [43], for example, proposed and analysed a dynamical system model (Equation (3)) to study the effect of depletion of forest biomass in a forested habitat caused by population pressure (industrialization) on the survival and existence of forest-dependent wildlife species. The model was developed with the assumptions that forest biomass, wildlife species, and population pressure are governed logistically; the density of forest biomass determines the density of wildlife species, and the growth rate coefficient increases as the biomass density of the resources grows; the carrying capacity of wildlife species is affected by the density of forest biomass and the density of industrialization pressure, with the former increasing and the later decreasing. The study suggests that, as the population pressure (industrialization) increases without control, the density of forest biomass decreases, leading to the decreasing of the density of wildlife species and its subsequent extinction. The analytical analysis provides important parameter threshold for the coexistence of all compartment involved in the interactions. This information is useful in policy formulation and implementation. However, the human population, which has a direct impact on forest biomass and wildlife species, was not included in the model formulation, and population pressure was not addressed as cumulative, instead relying solely on industrialization.

$$\begin{cases} \dfrac{dW}{dt} = r(B)W - \dfrac{r_0 N^2}{K(B,P)}, & N(0) = N_0 \geq 0, \\ \dfrac{dB}{dt} = r_1 W(B) - \dfrac{r_{10} B^2}{K_1(P)} - \alpha_1 PB, & B(0) = B_0 \geq 0, \\ \dfrac{dP}{dt} = r_2 P\left(1 - \dfrac{P}{L}\right) + \alpha_2 PB, & P(0) = P_0 \geq 0, \end{cases} \tag{3}$$

where $W(t)$, $B(t)$, and $P(t)$ are the cumulative density of wildlife species, the forest biomass, and population pressure, respectively.

In line with Bahadur et al. [43], Manju et al. [37] proposed a mathematical model (Equation (4)) to study the depletion of forest biomass due to industrialization pressure. The model was formulated based on the assumption that all functions are sufficiently smooth so that all solutions to initial value problems exist uniquely. Further, the densities of forest biomass and industrialization pressure were governed by logistic type equations as well as the forest carrying capacity depends on industrialization. The study considered ratio-dependent interactions with the assumption that in some cases it qualified to represent the reality than linear functional response models. However, the study did not describe precisely which cases ratio-dependent is the best interaction over the linear functional response.

$$\begin{cases} \dfrac{dB}{dt} = r(I)B - \dfrac{r_0 B^2}{K(I)} - \dfrac{\beta NB}{B + aI} - \dfrac{\alpha IB}{B + bW}, & B(0) = B_0 > 0, \\ \dfrac{dW}{dt} = -sW + \dfrac{\gamma IB}{B + bW}, & W(0) = W_0 > 0, \\ \dfrac{dI}{dt} = \omega I \left(1 - \dfrac{I}{L(B)}\right) + \dfrac{\delta WB}{B + aI}, & I(0) = I_0 > 0, \end{cases} \tag{4}$$

where $B(t)$, $W(t)$, and $I(t)$, respectively, are the density of forest biomass, wildlife species, and industrialization measure.

On the other hand, Kumari and Abhinav [27] developed and analysed a model (5) to study the survival of forest-dependent wildlife populations in the presence of population pressure-induced mining activities. The study used Holling-type II functional response to describe the interaction between forest and wildlife species, while the human population was thought to grow logistically. Conversely, population pressure and mining activities were assumed to be governed by mass action functional response. The study is aimed at addressing human-wildlife conflicts, which are the implication of overgrowing mining activities in the forest area. However, the effects of human-wildlife conflicts on human and wildlife populations were not explicitly captured in the model formulation. The model was analysed qualitatively for the boundedness, existence, and stability analysis of the boundary and interior equilibrium points, as well as the uniform persistence of the system. Furthermore, the quantitative analysis was performed to confirm the qualitative analysis, whereby the numerical results demonstrate that the system may not remain persistent if the utilisation rates of the forest are higher than its growth. The study further concluded that, in order to maintain the balance between the populations of humans and wildlife species, forest biomass that is inhabited by wildlife should be used sustainably.

$$\begin{cases} \dfrac{dB}{dt} = sB\left(1 - \dfrac{B}{L}\right) - \dfrac{\alpha_1 BW}{1 + \beta B} - \theta BN - \theta_1 B^2 M, & B(0) = B_0 \geq 0, \\ \dfrac{dW}{dt} = \dfrac{\beta_1 BW}{1 + \beta B} - \delta_0 W - \delta_W^2, & W(0) = W_0 \geq 0, \\ \dfrac{dN}{dt} = rN\left(1 - \dfrac{N}{K}\right) + \pi_1 \alpha_1 BN, & N(0) = N_0 \geq 0, \\ \dfrac{dP}{dt} = \lambda N - \lambda_0 P, & P(0) = P_0 \geq 0, \\ \dfrac{dM}{dt} = M_0 + \alpha P - \mu_0 M, & M(0) = M_0 \geq 0, \end{cases} \tag{5}$$

where $B(t)$, W, $N(t)$, $P(t)$, and $M(t)$ are the cumulative density of forest biomass, wildlife species, human population, population pressure, and mining activities, respectively.

Rachana et al. [40] developed and analysed a mathematical model (Equation (6)) to study the effect of deforestation caused by human population and industrialization on forest-dependent wildlife species. The growth rate of density of wildlife species that are entirely reliant on forest resources is governed by a logistic model, whose carrying capacity is depleted by human population and industrialization. The stability theory of nonlinear ordinary differential equations was used to study the local and global stability of the interior equilibrium point, as well as the system's persistence. According to findings, deforestation induced by population and industrialization is driving forest resources to extinction and endangering the survival of wildlife species. The numerical simulation was utilized to validate the findings of the analytical analysis, whereby critical parameters of the model were identified. Despite the model incorporates human and wildlife population as state variables, industrialization was treated as the sole source of human population pressure.

$$\begin{cases} \dfrac{dB}{dt} = sB - \dfrac{s_0 B^2}{L} - \alpha BN - \alpha_1 B^2 N - \beta BI - \beta_1 B^2 I - s_1 BW, & B(0) = B_0 \geq 0, \\ \dfrac{dN}{dt} = rN - \dfrac{r_0 N^2}{K} + \alpha BN + \alpha_1 B^2 N, & N(0) = N_0 \geq 0, \\ \dfrac{dI}{dt} = \beta BI + \beta_1 B^2 I - \beta_0 I^2 - \theta_0 I, & I(0) = I_0 \geq 0, \\ \dfrac{dW}{dt} = \pi s_1 BW - \phi_0 W^2 - (\phi_1 N + \phi_2 I) W^2 - \psi_0 W, & W(0) = W_0 \geq 0, \end{cases} \tag{6}$$

where $B(t)$, $N(t)$, $I(t)$, and $W(t)$ are the cumulative density of forest biomass, human population, industrialization, and wildlife species, respectively.

A year later, Kusum et al. [29] developed and analysed a nonlinear mathematical model (Equation (7)) to study the effect of deforestation caused by population and population pressure on wildlife species. The model considered a forest habitat where both forest biomass and wildlife species are under threat due to overgrowing human population and their demands. The formulation of the model was based on the assumptions that wildlife species are completely reliant on forestry resources for food and shelter. Because of the desire for agricultural land for food production, wood, space for housing complexes, and economic position, wildlife species are being affected as the human population expands in the forest region. The findings show that the density of wildlife species tends to decline as the parameters responsible for the increase of population pressure increase. Although population pressure affects wildlife populations, the model did not take into account how wildlife population benefits human population.

$$\begin{cases} \dfrac{dB}{dt} = sB\left(1-\dfrac{B}{L}\right) - \alpha_1 BN - \alpha_2 B^2 P - \phi BW, & B(0)=B_0 \geq 0, \\ \dfrac{dN}{dt} = rN\left(1-\dfrac{N}{K}\right) + \pi_1 \alpha_1 BN, & N(0)=N_0 \geq 0, \\ \dfrac{dP}{dt} = \lambda N - \lambda_0 P, & P(0)=P_0 \geq 0, \\ \dfrac{dW}{dt} = \theta\phi BW - \delta_0 W^2 - \theta_1 PW - \delta_1 W^2 P - \theta_0 W, & W(0)=W_0 \geq 0, \end{cases} \tag{7}$$

where $B(t)$, $N(t)$, $P(t)$, and $W(t)$ are the cumulative density of forest biomass, human population, population pressure, and wildlife species.

Recently, Rachana et al. [44] developed and analysed a model (Equation (8)) to study the impact of human activities on forest biomass and the wildlife population. The study assumed that the growth rate of the wildlife population wholly depends on forest for food and shelter. Further, it was assumed that the growth of forest biomass and human population follows a logistic nonlinear type of equations. The findings show that there is a strong relationship between human activities and forest resources. As to other studies reviewed, Rachana et al.'s [44] study did not include the concept of the residence-based human population which is a critical phenomenon in forest management in developing countries [20].

$$\begin{cases} \dfrac{dB}{dt} = sB - \dfrac{s_0 B^2}{L} - \alpha BW - \beta BN - \gamma B^2 H, & B(0)=B_0 \geq 0, \\ \dfrac{dW}{dt} = \theta_1 \alpha BW - \delta_1 W - \delta_0 W^2 - \nu_1 WN - \nu_1 WH, & W(0)=W_0 \geq 0, \\ \dfrac{dN}{dt} = rN - \dfrac{r_0 N^2}{K} + \theta_2 \beta FN - \sigma NW, & N(0)=N_0 \geq 0, \\ \dfrac{dH}{dt} = \lambda N + \theta_3 \gamma B^2 H - \mu_0 H, & H(0)=H_0 \geq 0, \end{cases} \tag{8}$$

where $B(t)$, $N(t)$, $H(t)$, and $W(t)$ are the cumulative density of forest biomass, human population, human activities, and wildlife species, respectively.

Apart from models that studies depletion of forest biomass and forest-dependent wildlife species, different scholars ([1, 38, 45, 46]) developed and analysed models for depletion and conservation of forest biomass; the impact of forest depletion on the survival of other biological species was not featured in modelling process. For example, Kumar et al. [38] developed and analysed a model (Equation (9)) to study the impact of population and population pressure on forest resources and its conservation by using economic measures. The model was developed with the assumption that the growth of forest biomass and human population were governed by logistic equation, while industrialization, population pressure, and economic measures were governed by mass action functional response. Further, it was assumed that the demands for industrial products increase the intensity of industrialization and eventually destroy forest biomass. Economic measures were therefore assumed to be implemented to lessen the severity of population pressure, which eventually reduce the intensity of industrialization. Although the study incorporates human population as one of the state variables, it does not explore how the decline in forest biomass affects the survival of other biological species. The model analysis suggests that the application of economic measures can significantly reduce population pressure and conserve forest resources if they are applied with enough potential.

$$\begin{cases} \dfrac{dB}{dt} = sB\left(1 - \dfrac{B}{L}\right) - \alpha BN - \alpha_1 B^2 N - \beta BI - \beta_2 B^2 I, & B(0) = B_0 \geq 0, \\ \dfrac{dN}{dt} = rN\left(1 - \dfrac{N}{K}\right) + \pi\alpha BN + \pi_1 \alpha_1 B^2 N, & N(0) = N_0 \geq 0, \\ \dfrac{dP}{dt} = \lambda N - \lambda_1 P - \lambda_0 P - \lambda_2 PE, & P(0) = P_0 \geq 0, \\ \dfrac{dI}{dt} = \nu_1 \lambda_1 P + \theta\beta BI + \theta_1 \beta_1 B^2 I - \theta_0 I - \theta_m I^2, & I(0) = I_0 \geq 0, \\ \dfrac{dE}{dt} = \psi P - \psi_0 E, & E(0) = E_0 \geq 0, \end{cases} \tag{9}$$

where $B(t)$, $N(t)$, $P(t)$, $I(t)$, and $E(t)$ are the cumulative density of forest biomass, human population, population pressure, cumulative density of industrialization, and economic measures, respectively.

Other scholars [45, 47, 48] tried to understand the contribution of environment pollution as the result of human activities on the depletion of forest biomass and the survival of forest-dependent wildlife species. For example, Balram and Jabir [36] developed and analysed a mathematical model (Equation (10)) to study the impact of environmental pollution on forest biomass. The model was formulated by assuming that forest biomass is depleted by pollution in a closed region D with a smooth boundary ∂D. The study assumed that the pollutant from the environment does not affect the forest resources directly. Conversely, the uptake pollutant is converted to other toxic substance through some metabolic process; this substance is what affects the growth rate of the forest biomass. The results show that if the time delay in formation of this toxic substance is large enough, then the effects of environmental pollution on forest biomass will be minimized. However, if the rate toxic substance formation is high, then the system will destabilize.

$$\begin{cases} \dfrac{\partial B}{\partial t} = r(C)B - \dfrac{r_0 B^2}{K(T)} + D_1 \nabla^2 B, & B(x, y, 0) = B_0(x, y) \geq 0, \\ \dfrac{\partial T}{\partial t} = Q(t) - \delta_0 T - \alpha_1 BT + D_2 \nabla^2 T, & T(x, y, 0) = T_0(x, y) \geq 0, \\ \dfrac{\partial U}{\partial t} = -\delta_1 U + \alpha_1 BT, & U(x, y, 0) = U_0(x, y) \geq 0, \\ \dfrac{\partial C}{\partial t} = \alpha U - \alpha_0 C, & C(x, y, 0) = C_0(x, y) \geq 0, \end{cases} \tag{10}$$

such that

$$\begin{gathered} (x, y) \in D, \\ t \geq 0. \end{gathered} \tag{11}$$

The variables $B(t)$, $T(t)$, $U(t)$, and $C(t)$ are the density of forest biomass, concentration of pollutants in the environment, environmental pollution concentration absorbed by the resource biomass at coordinates $(x, y) \in D$ and time $t \geq 0$ and concentration of toxic substance formed after conversion of pollutant $U(t)$, respectively.

3.2. Other Models. Apart from dynamical models, discrete, stochastic, and data analysis models are also used to study the impact of population and population pressure on biodiversity. For example, Freitas et al. [49] studied the effects of human activities on forest cover dynamics, specifically, they were interested to understand if forest fragmentation, deforestation, and forest regrowth can be defined by topography, roads density, and land use. The generalized least squares regression models were used to fit the data, and the findings showed that road density has a long-term effect on forest cover and are an attractor of topography change. Thus, where the density of roads is high, forests are at risk. They recommended that effective forest management strategies would be well served to consider how roads are distributed.

Vanessa et al. [50] used regression models to investigate the relationship between anthropogenic disturbance and forest characteristics. Fourteen attributes related to population pressure were selected as predictor variables while, seven forest attributes related to species diversity, composition, and structure were response variables. The study backed the evidence that human activities at different spatial scales disrupt the structure and composition of the forest cover. Furthermore, the study shows that the percentage of endangered species is positively correlated to long road networks and logging.

Ali and Maryam [32] developed Multilayer Perceptron Neural Network (MLP) to predict vegetation diversity under ecological conditions and human activities. Mean Absolute Error (MAE) (Equation (12)), Mean Square Error (MSE) (Equation (13)), and Coefficient of determination (R^2) (Equation (14)) indices were used to estimate the accuracy and performance of the model [51].

$$\text{MAE} = \frac{\sum_1^n (O_i - P_i)^2}{n}, \tag{12}$$

$$\text{MSE} = \frac{\sum_1^n |O_i - P_i|}{n}, \tag{13}$$

$$R^2 = \frac{\sum_1^n (P_i - O_{\text{ave}})^2}{\sum_1^n (O_i - O_{\text{ave}})^2}, \tag{14}$$

where O_i is the observed data, P_i is the predicted data, O_{ave} is the mean of the observed data, and n is the number of samples. The MLP model demonstrates the capability of predicting the impact of human activities on vegetation diversity, but with the challenge of identification and quantification of the influential variable. In line with this study, Ali et al. [31] developed a model for assessing vegetation density in protected areas which are threatened by tourism activities. The study used data mining techniques in which the results reveal that the MPL has the ability to predict vegetation density changes under tourism pressure precisely compared to Radial Basis Function Neural Network (RBFNN) and Support Vector Machine (SVM) models. In additional, the model suggested that the area with higher organic matter and soil moisture are likely to tolerate pressure form tourist activities. The use of data mining techniques in this study proved to be the best approach when we are confronting with unavailability of real data. Further, Mauro and Gerardo [52] used quantitative analysis to study the sustainability of the world human population given deforestation stance. They employed a simplified model based on the stochastic process influenced by a random walk continuous time in combination with a dynamical model that describes human-forest interaction. From the statistical point of view, they showed that, given the growing demands of forest resources, if no action will be taken, the probability that forest resources will accommodate the growing demands of human population is less than 10% in the most optimistic scenario. Yet, the model has limitations due to the use of a simple dynamical model which excludes many variables and parameters, however, it provides a good foundation for incorporating dynamical and stochastic models in addressing environmental issues. Zelin et al. [53] and Isaiah et al. [54] provide an in-depth review of the use of other models in studying human-forest interaction.

4. Discussion and Conclusion

From this review, it is true that the use of mathematical models specifically the systems of differential equations have continually attracted many researchers in the field of forest management. The growing interest hinges on its potential to untangle the complex phenomenon resulted from human-nature interactions and provide tools and information that support the formulation of policies and strategies that aim to conserve forest biomass. Despite the limitations associated with many assumptions in mathematical modelling, especially dynamical system models, through analytical and numerical analysis, the review depicted that, key modelling questions were addressed, that is, the behaviour of the human-forest interaction, what are the parameters that needs attention by policymakers, and the reliability of the developed model. In the same vein, the use of data mining techniques [31, 32, 52], on the other hand, recently demonstrated its applicability to study the impact of human population and its associated activities on the density of forest biomass in light of the lack of sufficient datasets and unlimited parameters that influence the model outputs.

The natural and social world is dynamic, which is necessitating the need for iterative efforts to find better models to improve forest management. This review identified the potential areas of improving the existed models, the areas ranging from model formulation to model analysis (analytical and numerical). Regarding to model formulation, the review elucidates the need for developing a complex and more relevant model to understand and predict the impact of anthropogenic activities on forest biomass and forest-dependent wildlife species under the current growing population pressure, changing climatic conditions and socioeconomic situations. It is believed that the households' income determines the consumption patterns of the forest resource and human lifestyles [20]. On the other hand, there is unequal distribution of per capital income between rural areas and urban, where rural areas account for more poor households than urban areas [23]. To address the role of socioeconomic aspects on forest management, the developed models must incorporate partition of human populations (rural and urban) variable to capture important information regarding the conservation or forest. Partitioning of human population will accommodate emerging socioeconomic and ecological variables that hold together the human-nature interaction and relationships.

Regarding model analysis, the theory of Lyapunov's function was used to establish global asymptotic behaviour of the system in most of the reviewed works. This approach has a shortfall as there is no systematic way to choose proper candidate of the Lyapunov function [55], its effectiveness is mostly depend on trial and error as well as specific problems. The researchers believe that there is a potential to use the Volterra-Lyapunov stable matrices [56] method especially for models with few number of variables. The method incorporates the Volterra matrix theory into the Lyapunov functions which avoids the necessity to determine the coefficients of the Lyapunov functions under specific conditions [55]. Furthermore, mathematical models are known to have input parameters which are not known and with sufficient degree of uncertainty due to natural variation and errors in measurement and parameter estimation. It is equally important to perform uncertainty quantification of the model input parameters to quantify the uncertainty and identify which parameters are more sensitive to the model output. The reviewed works used either single parameter or local sensitivity methods to perform uncertainty quantification. These methods keep all other parameters fixed at default values which makes the methods inadequately in measuring the uncertainty and sensitivity of the input parameter [57]. Therefore, there is a potential of using a multidimensional parameter space uncertainty quantification methods such as Latin Hypercube Sampling and Partial Rank Correlation Coefficient (LHS/PRCC) and Extended Fourier Amplitude Sensitivity Test (eFAST) [58]. These methods are correlational and variance-based approach, respectively, and have recently proved to have the ability to perform global uncertainty quantification where by all uncertainty can be identified and quantified while all parameters are simultaneously varied.

Data Availability

No underlying data was collected or produced in this study.

Conflicts of Interest

The authors declare that this work does not have any conflicts of interest.

Authors' Contributions

Ibrahim M Fanuel was responsible for the conceptualization, writing the original draft, reviewing and editing, and approved the final version for submission. Francis Moyo and Damian Kajunguri worked on the conceptualization, supervised the study, revised the manuscript critically, reviewing and editing, and approved the final version for submission.

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References

[1] M. A. Kumar and L. Kusum, "Depletion and conservation of forestry resources: a mathematical model," *Differential Equations and Dynamical Systems*, vol. 23, no. 1, pp. 25–41, 2013.

[2] P. Prabir, "Is the forest biomass a key regulator of global warming?: a mathematical modelling study," *Geology, Ecology, and Landscapes*, vol. 6, no. 1, pp. 66–74, 2020.

[3] S. P. Kumar, *Environmental Management: Issues and Concerns in Developing Countries*, Springer International Publishing, 1 ed. edition, 2021.

[4] H. Z. Chi, K. Chiho, and S. Osamu, "Interaction between rural people's basic needs and forest products: a case study of the Katha district of Myanmar," *International Journal of Forestry Research*, vol. 2017, Article ID 2105012, 18 pages, 2017.

[5] K. J. Ramadhani, "Realities on deforestation in Tanzania: trends, drivers, implications and the way forward," in *Precious Forests*, Intech Open, 1 ed. edition, 2015.

[6] FAO, *State of the World's Forests; Enhancing the Socio-Economic Benefits from Forests. Technical Report*, FAO Rome, 2014.

[7] S. Carl, "A review of endemic species in the eastern arc Afromontane region: importance, inferences, and conservation," *Macalester Reviews in Biogeography*, vol. 1, no. 1, pp. 1–20, 2008.

[8] D. L. Michel and D. Luc, "Sustainable management of natural resources: mathematical models and methods," in *Environmental Science and Engineering*, Springer Science & Business Media, 2008.

[9] R. Abdul, M. Hengyun, A. Munir, I. Muhammad, T. Ousmane, and C. A. Ali, "Towards environmental sustainability: devolving the influence of carbon dioxide emission to population growth, climate change, forestry, livestock and crops production in Pakistan," *Ecological Indicators*, vol. 125, pp. 1–11, 2021.

[10] A. Alfred and A. Haidari, *Population Growth, Structure and Momentum in Tanzania*, The Economic and Social Research Foundation (ESRF), 2014, Technical Report ESRF discussion paper 61:.

[11] B. Tombari, G. B. Gbidum, and S. K. Joy, "Deforestation: human causes, consequences and possible solution," *Journal of Geographical Research*, vol. 4, no. 2, pp. 22–30, 2021.

[12] K. Pushpam and Y. Makiko, "The marginal poor and their dependence on ecosystem services: evidence from South Asia and sub-Saharan Africa," in *Marginality: Addressing the Nexus of Poverty, Exclusion and Ecology*, pp. 169–180, Springer, Dordrecht, 1 ed. edition, 2014.

[13] M. M. Shadrack, K. Joseph, M. Simon, and L. Isack, "Energy sources for cooking and its determinants in rural areas of Tanzania," *Independent Journal of Management & Production*, vol. 10, no. 3, pp. 934–950, 2019.

[14] FAO and UNEP, "The state of the world's forests 2020," in *Forests, Biodiversity and People*, Technical Report: FAO, 2020.

[15] M. Mahmoud and C. Paula, "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss," *UN Chronicle*, vol. 51, no. 4, pp. 34-35, 2015.

[16] L. Zhang, E. I. Ameca, B. Otero-Jimenez et al., "Human-induced deforestation increases extinction risk faster than climate pressures: evidence from long-term monitoring of the globally endangered Milne-Edward's sifaka," *Biological Conservation*, vol. 274, article 109716, 2022.

[17] B. Duncan, "Sustainable consumption and production of forest products," in *Proceedings of the Thirteenth Session of the United Nations Forum on Forests*, pp. 7–11, New York, USA, 2018.

[18] G. Bhardwaj, "How poverty is contributing to deforestation across Africa," 2018, http://www.chathamhouse.org/2018/12/howpoverty-contributing-deforestation-across-africa.

[19] W. Robert, "Deforestation and economic development," *Canadian Journal of Regional Science*, vol. 16, no. 3, pp. 481–497, 1993.

[20] O. Raphael, K. J. Ndzifon, and M. Francis, "Community-based forest landscape restoration (FLR): determinants and policy implications in Tanzania," *Land Use Policy*, vol. 109, article 105664, 2021.

[21] W. Divyanshi, "The number of extremely poor people continues to rise in sub–Saharan Africa," 2018, https://blogs.worldbank.org/opendata/number-extremely-poor-people-continues-rise-sub-saharan-africa.

[22] World Bank, *Tanzania Mainland Poverty Assessment*, World Bank, Washington, DC, Technical Report, 2019.

[23] NBS, *TheUnited Republic of Tanzania Key Findings 2011/12 Household Budget Survey,Technical Report:*, NBS–Tanzania, 2013.

[24] MNRT, *National Forest Resources Monitoring and Assessment of Tanzania Mainland (NAFORMA): Main Results Report. Technical Report*, MNRTDar es Salaam, Tanzania, 2015.

[25] A. Manju and P. Rachana, "Conservation of forestry biomass and wildlife population: a mathematical model," *Asian Journal of Mathematics and Computer Research*, vol. 4, no. 1, pp. 1–15, 2015.

[26] L. Kusum and M. A. Kumar, "Modeling the effect of economic efforts to control population pressure and conserve forestry resources," *Nonlinear Analysis-Modelling and Control*, vol. 22, no. 4, pp. 473–488, 2017.

[27] J. Kumari and T. Abhinav, "A mathematical model to study the impact of mining activities and pollution on forest resources and wildlife population," *Journal of Biological Systems*, vol. 25, no. 2, pp. 207–230, 2017.

[28] T. Abhinav, J. Kumari, and D. Susanto, "A mathematical model to investigate the impact of overgrowing population-induced mining on forest resources," *Environment, Development and Sustainability*, vol. 20, no. 4, pp. 1499–1516, 2018.

[29] L. Kusum, M. A. Kumar, and S. J. Bahadur, “Modeling the effect of deforestation caused by human population pressure on wildlife species,” *Nonlinear Analysis: Modelling and Control*, vol. 23, no. 3, pp. 303–320, 2018.

[30] P. Andhika, Z. R. Nur, A. Nursanti, and S. Asep, “A mathematical model to study the effects of population pressure on two–patch forest resources,” *AIP Conference Proceedings*, vol. 2264, no. 1, article 050003, 2020.

[31] J. Ali, G. Hamid, and S. Maryam, “Tourism impact assessment modeling of vegetation density for protected areas using data mining techniques,” *Land Degradation & Development*, vol. 31, no. 12, pp. 1502–1519, 2020.

[32] J. Ali and S. Maryam, “Human activities impact prediction in vegetation diversity of Lar national park in Iran using artificial neural network model,” *Integrated Environmental Assessment and Management*, vol. 17, no. 1, pp. 42–52, 2021.

[33] M. Timothy, “Selecting studies for systemic review: inclusion and exclusion criteria,” *Contemporary Issues in Communication Science and Disorders*, vol. 33, no. Spring, pp. 21–27, 2006.

[34] B. Joseph and G. Keith, *Decision Methods for Forest Resource Management*, Academic Press, 1 ed. edition, 2003.

[35] Freedman Herbert Irving, “Deterministic mathematical models in population ecology,” in *Pure & Applied Mathematics*, vol. 57, Marcel Dekker Incorporated, 1980.

[36] D. Balram and H. Jabir, “Models for the effect of environmental pollution on forestry resources with time delay,” *Nonlinear Analysis: Real World Applications*, vol. 5, no. 3, pp. 549–570, 2004.

[37] A. Manju, F. Tazeen, and F. H. Irving, “Depletion of forestry resource biomass due to industrialization pressure: a ratio–dependent mathematical model,” *Journal of Biological Dynamics*, vol. 4, no. 4, pp. 381–396, 2010.

[38] M. A. Kumar, L. Kusum, and S. J. Bahadur, “A mathematical model for the depletion of forestry resources due to population and population pressure augmented industrialization,” *International Journal of Modeling, Simulation, and Scientific Computing*, vol. 5, no. 1, pp. 1–16, 2014.

[39] M. A. Kumar and L. Kusum, “A mathematical model to achieve sustainable forest management,” *International Journal of Modeling, Simulation, and Scientific Computing*, vol. 6, no. 4, pp. 1–18, 2015.

[40] P. Rachana, A. Manju, T. Yasuhiro, and S. J. Bahadur, “Modeling the depletion of forest resources due to population and industrialization and its effect on survival of wildlife species,” *International Journal of Mathematical Modelling and Analysis of Complex Systems (IJMMACS): Nature and Society*, vol. 3, no. 1, pp. 37–65, 2017.

[41] S. S. Kumari, P. Jayantika, and J. Kumari, “A dynamical study on the adverse effects of industrial activities in the forest and wildlife region through modelling,” *Modeling Earth Systems and Environment*, vol. 8, no. 4, pp. 1–13, 2022.

[42] B. Fred, *Castillo-Chavez Carlos. Mathematical Models in Population Biology and Epidemiology*, Springer, 2 ed. edition, 2012.

[43] S. J. Bahadur, D. Balram, and F. H. Irving, “Effect of changing habitat on survival of species,” *Ecological Modelling*, vol. 87, no. 3, pp. 205–216, 1996.

[44] P. Rachana, V. Vinay, and A. Manju, “Impact of human activities on forest resources and wildlife population,” *Computational Ecology and Software*, vol. 11, no. 2, pp. 83–99, 2021.

[45] S. J. Bahadur and D. Balram, “Modelling the depletion and conservation of forestry resources: effects of population and pollution,” *Journal of Mathematical Biology*, vol. 36, no. 1, pp. 71–94, 1997.

[46] G. M. Demsie and E. M. Fentahun, “Mathematical modeling on conservation of depleted forestry resources,” *Natural Resource Modeling*, vol. 35, no. 2, article e12338, 2022.

[47] D. Balram, “Modelling effects of industrialization, population and pollution on a renewable resource,” *Nonlinear Analysis: Real World Applications*, vol. 11, no. 4, pp. 2833–2848, 2010.

[48] D. Balram, U. R. Kumar, and H. Jabir, “Effects of industrialization and pollution on resource biomass: a mathematical model,” *Ecological Modelling*, vol. 167, no. 1-2, pp. 83–95, 2003.

[49] S. R. Freitas, T. J. Hawbaker, and J. P. Metzger, “Effects of roads, topography, and land use on forest cover dynamics in the Brazilian Atlantic Forest,” *Forest Ecology and Management*, vol. 259, no. 3, pp. 410–417, 2010.

[50] L. D. Vanessa, R. A. Vinicius, O. L. Zimermann, D. G. A. Luis, and V. A. Christian, “Modelling changes in forest attributes driven by human activities at different spatial scales in the subtropical Atlantic Forest,” *Biodiversity and Conservation*, vol. 29, no. 4, pp. 1283–1299, 2020.

[51] K. Saba, J. Ali, P. Reza, and B. Zahra, “Application of ANN modeling techniques in the prediction of the diameter of PCL/gelatin nanofibers in environmental and medical studies,” *RSC Advances*, vol. 9, no. 43, pp. 24858–24874, 2019.

[52] B. Mauro and A. Gerardo, “Deforestation and world population sustainability: a quantitative analysis,” *Scientific Reports*, vol. 10, no. 1, pp. 1–9, 2020.

[53] L. Zelin, P. Changhui, W. Timothy, C. Jean-Noel, D. R. Annie, and K. Daniel, “Application of machine-learning methods in forest ecology: recent progress and future challenges,” *Environmental Reviews*, vol. 26, no. 4, pp. 339–350, 2018.

[54] F. Isaiah, B. Chris, and A. Madhur, “Modelling coupled human–environment complexity for the future of the biosphere: strengths, gaps and promising directions,” *Philosophical Transactions of the Royal Society B*, vol. 377, no. 1857, pp. 1–13, 2022.

[55] C. Fengsheng and S. Stanford, “Volterra–Lyapunov stability analysis of the aolutions of babesiosis disease model,” *Symmetry*, vol. 13, no. 7, pp. 1–14, 2021.

[56] R. Fabio, “Global stability results for epidemic models with latent period,” *IMA Journal of Mathematical Medicine and Biology*, vol. 7, no. 2, pp. 69–75, 1990.

[57] M. Simeone, H. Ian, R. Christian, and K. Denise, “A methodology for performing global uncertainty and sensitivity analysis in systems biology,” *Journal of Theoretical Biology*, vol. 254, no. 1, pp. 178–196, 2008.

[58] H. Toshimitsu and S. Andrea, “Importance measures in global sensitivity analysis of nonlinear models,” *Reliability Engineering & System Safety*, vol. 52, no. 1, pp. 1–17, 1996.