

Mathematical Model of Conservation Strategies for the Rare Plant: A Society-Inclusive Dynamic Model



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<https://doi.org/10.18280/mmep.130204>

ABSTRACT

Received: 8 September 2025

Revised: 3 November 2025

Accepted: 12 November 2025

Available online: 15 March 2026

Keywords:

mathematical modelling, conservation strategy, society-inclusive, dynamic model, *Amorphophallus gigas*, biodiversity conservation, socio-ecological systems

Biodiversity loss poses severe challenges for conserving rare species, particularly in socio-ecological landscapes where human livelihoods depend on natural resources. This study proposes a society-inclusive dynamic model to evaluate conservation strategies for *Amorphophallus gigas*, a rare plant species found in North Sumatra, Indonesia. The model integrates ecological dynamics, community participation, and governance support into a coupled system of nonlinear ordinary differential equations, which are numerically solved using a Runge–Kutta scheme and enhanced by an optimization framework. Two scenarios were simulated over a 100-year horizon. Under baseline conditions without interventions, the population only grows modestly to ~180 individuals, ecological health stabilizes at ~0.55, and community involvement remains low (~0.45). With government regulation and support, the population rises to ~620 individuals, ecological health improves to ~0.85, socioeconomic benefits increase to ~0.75, and community involvement grows to ~0.80. These results demonstrate that aligning ecological goals with policy measures and incentive-driven community programs creates positive feedbacks that sustain biodiversity while improving livelihoods. The study contributes a quantitative framework that explicitly incorporates human dimensions into conservation modeling. Limitations include the use of simplified spatial dynamics and the exclusion of climate change factors, highlighting the need for future extensions toward more realistic applications.

1. INTRODUCTION

Biodiversity loss is a pressing global issue, with many species facing unprecedented risks of extinction due to habitat destruction, overexploitation, and climate change [1-3]. Rare plant species are among the most vulnerable, as their restricted distribution and ecological specialization make them particularly sensitive to environmental changes. Yet, these plants often play critical roles in ecosystem stability and resilience, as well as in sustaining human livelihoods.

Conservation of rare plants is therefore not only an ecological necessity but also a socio-economic challenge. Effective strategies must balance biodiversity protection with the needs of local communities that depend on plant resources for food, income, and cultural purposes [4-6]. Achieving this balance requires approaches that go beyond traditional conservation models and incorporate the perspectives of multiple stakeholders.

One such species is *Amorphophallus gigas*, a rare giant plant endemic to parts of North Sumatra, Indonesia. It is found in the Simandiingin Hamlet, Sungai Kanan District, where its

tubers are widely used as an important local food source. The plant has ecological, cultural, and economic significance for surrounding communities. However, its population is under increasing threat due to land conversion, agricultural expansion, and unsustainable harvesting practices [7-9].

The situation of *Amorphophallus gigas* reflects a broader challenge: how to conserve rare species in landscapes where human activities and ecological systems are deeply intertwined. Protected areas remain a cornerstone of conservation [3], but in practice, they are often insufficient to prevent biodiversity decline. Studies have highlighted the need to manage conflicts between conservation and human development, which requires more integrative approaches [10, 11].

Previous modeling studies have provided valuable insights into ecological dynamics, land-use conflicts, and biodiversity management. However, most of these approaches have emphasized ecological factors while neglecting social and governance dimensions [10, 11]. As a result, they fall short in capturing the complexity of socio-ecological systems where conservation outcomes depend not only on biological

processes but also on human behavior and policy interventions.

This study seeks to address this gap by developing a society-inclusive dynamic model that explicitly integrates ecological, socioeconomic, and governance components. The model captures the interactions between plant population growth, community involvement, ecological health, and conservation policies. Unlike traditional ‘fences and fines’ strategies [12], it adopts a more inclusive perspective, recognizing that conservation success requires aligning ecological goals with community interests.

The case study of *Amorphophallus gigas* in North Sumatra provides a unique opportunity to apply and test this modeling framework. By simulating scenarios with and without conservation interventions, the model evaluates how strategies such as protected area designation, incentive-based community programs, and regulated resource extraction influence long-term plant persistence and human wellbeing. The integration of field data and parameter estimates ensures that the model reflects local realities [5, 8, 9, 13].

Finally, this study makes three contributions. First, it develops a coupled system of ordinary differential equations (ODEs) to represent socio-ecological interactions. Second, it applies the model to simulate conservation and policy scenarios over a century-long horizon. Third, it employs optimization techniques to identify strategies that maximize both ecological and social outcomes [11, 14]. In doing so, the research advances the integration of human dimensions into mathematical conservation models and provides insights for policy design and community-based biodiversity management [6, 15-18].

2. METHODOLOGY

This study employed a dynamic, society-inclusive mathematical model to examine conservation strategies for the rare plant *Amorphophallus gigas* in Simandiangan Hamlet, Sungai Kanan District, North Sumatra, Indonesia. The model integrates ecological, spatial, and socioeconomic dimensions, recognizing that the persistence of rare plants depends not only on biological growth but also on human behavior and conservation policies. The main purpose of the model is to simulate population dynamics under different management scenarios and to identify conservation strategies that simultaneously support ecological resilience and community wellbeing.

The framework of the model consists of three interconnected components. The first is the ecological component, which represents the biological processes of *Amorphophallus gigas*, including growth, reproduction, mortality, and the effects of habitat quality. The second is the spatial component, which describes land use and land cover changes driven by agricultural expansion, human population growth, and resource extraction. The third is the socioeconomic component, which captures household livelihoods, harvesting practices, decision-making, and levels of community participation in conservation programs. Together, these components form a system with multiple feedback loops that link ecological health, community behavior, and conservation outcomes.

Several assumptions were introduced to maintain tractability. The growth rate of the plant population is assumed to be constant at 10% per year, while the extinction rate is set at 2.5% per year. The initial population size in 2023 is

estimated to be 92 individuals, based on field observations [19]. Habitat quality is assumed to decline proportionally with land conversion but improve under conservation interventions such as restoration and protection. Community involvement in conservation is represented as a continuous variable ranging between 0 and 1, where higher values indicate stronger engagement. Finally, government regulation and support are treated as external drivers that can either positively or negatively influence conservation outcomes.

The ecological sub-model is formalized using a recurrence relation for population size:

$$P(N) = \{(1 + r)N.P(0)\} - m.\{(1 + r)N - 1.P(0)\} \quad (1)$$

where,

$P(0)$ = Current population of *Amorphophallus gigas*

$P(N)$ = Total population of *Amorphophallus gigas* in the N th year

r = Average population growth rate of *Amorphophallus gigas* per year

m = Average extinction of the *Amorphophallus gigas* population per year

Substituting parameter values gives:

$$P(N) = (1 + 0.1)^N.P(0) - 0.025[(1 + 0.1)^{N-1}P(0)] \quad (2)$$

This formulation predicts that the population will grow from 92 individuals in 2023 to approximately 99 individuals in 2024, and to around 619 individuals by 2045, under the assumption of constant growth and extinction rates [20].

The spatial sub-model accounts for land use change and habitat degradation. Habitat quality is modeled as a dynamic index that influences the carrying capacity of the population. The carrying capacity is expressed as:

$$K(t) = K_{max}.H(t) \quad (3)$$

where, K_{max} is the maximum carrying capacity under intact habitat, and $H(t)$ is the habitat quality index, ranging from 0 to 1. Habitat declines as land conversion increases, while restoration or protection can increase habitat quality. Remote sensing analysis and land cover data were used to parameterize this component [21, 22].

The socioeconomic sub-model describes community behavior, economic benefits, and participation in conservation. Community involvement is modeled dynamically as a function of socioeconomic benefits, ecological costs, and external incentives:

$$\frac{dC}{dt} = \lambda C(1 - C) + \mu S - \nu E \quad (4)$$

where, C is community involvement, λ is the intrinsic growth rate of participation, S represents socioeconomic benefits, E represents ecological costs, and μ, ν are coefficients linking benefits and costs to participation. This representation allows the evaluation of strategies such as incentive schemes, payments for ecosystem services, or community-based land use planning [6-8].

The complete model was implemented in Python. A fourth-order Runge–Kutta algorithm was used to solve the system of ODEs numerically. The simulation horizon was set at 100 years, covering the period from 2023 to 2123, in order to capture long-term dynamics. Initial conditions were based on field surveys, while parameter values were derived from both

literature and empirical studies [19-22]. The computational framework allows flexible testing of conservation policies, including habitat restoration, sustainable harvesting, and incentive-based conservation programs.

Two main scenarios were evaluated. The baseline scenario represents the case without any conservation interventions, where population dynamics are driven solely by natural growth, mortality, and ongoing habitat loss. This reflects a “business-as-usual” trajectory. In contrast, the government intervention scenario introduces regulatory measures, community incentives, and conservation support. This includes protected area designation, regulated harvesting, and programs designed to enhance community participation. By comparing these two scenarios, the model provides insights into the effectiveness of different strategies in balancing ecological persistence and socioeconomic benefits.

3. RESULTS AND DISCUSSION

The model results highlight the complex interactions between ecological, socioeconomic, and policy variables in shaping the long-term persistence of *Amorphophallus gigas*. Without targeted conservation efforts, the population in Simandiangan Hamlet is projected to decline, while interventions incorporating community engagement and government support significantly improve both ecological and social outcomes. To capture these dynamics, the most dominant variables in the community-inclusive system were selected and are summarized in Table 1.

Table 1. Rare plants conservation factors

Variable	Description	Scale
R	Rare plant population size (<i>Amorphophallus gigas</i>)	$R \geq 0$
C	Community involvement level	$0 \leq C \leq 1$
E	Environmental quality index	$0 \leq E \leq 1$
S	Ecological health index	$0 \leq S \leq 1$
T	Socio-Economic benefits to local communities	$0 \leq T \leq 1$
P	Conservation efforts intensity	$0 \leq P \leq 1$
G	Government regulation level	$0 \leq G \leq 1$
M	Government support level	$0 \leq M \leq 1$

The model formulation includes multiple interacting components. The ecological sub-model captures plant growth, ecological health depends on both population size and conservation activities, while community and socioeconomic sub-models account for participation levels and benefits. Government regulation and support are included as additional drivers. The governing equations are shown below:

• **Ecological component**

Rare plant population growth:

$$\frac{dP}{dt} = rP \left(1 - \frac{P}{K}\right) + \alpha C - \beta T + \psi G \quad (5)$$

Ecological health dynamics:

$$\frac{dE}{dt} = \gamma E + \delta P - \varepsilon T - \xi M \quad (6)$$

• **Socioeconomic component**

Community involvement dynamics:

$$\frac{dC}{dt} = \lambda C + \mu S - \nu T + \nu M \quad (7)$$

Socio-economic benefits dynamics:

$$\frac{dS}{dt} = \eta S + \kappa P - \zeta C \quad (8)$$

• **Conservation efforts component**

Conservation efforts dynamics:

$$\frac{dT}{dt} = \pi T + \rho P - \sigma E - \omega G \quad (9)$$

• **Government intervention component**

Government regulation dynamics:

$$\frac{dG}{dt} = \phi G + \psi P - \omega T \quad (10)$$

Government support dynamics:

$$\frac{dM}{dt} = \tau M + \nu C - \xi E \quad (11)$$

The values of all parameters used in the simulation are presented in Table 2.

Table 2. The parameter values of the conservation model

Parameter	Description	Value (per year)
r	Intrinsic growth rate of rare plant	10%
K	Carrying capacity of the rare plant	800 individuals
α	Community involvement coefficient on plant growth	0.05
β	Conservation efforts coefficient on plant growth	0.01
γ	Ecological health growth rate	0.1
δ	Plant population coefficient on ecological health	0.02
ε	Conservation efforts coefficient on ecological health	0.005
λ	Community involvement growth rate	0.2
μ	Socio-economic benefits coefficient on community involvement	0.1
ν	Conservation efforts coefficient on community involvement	0.005
η	Socio-economic benefits growth rate	0.2
κ	Plant population coefficient on socio-economic benefits	0.01
ζ	Community involvement coefficient on socio-economic benefits	0.005
π	Conservation efforts growth rate	0.1
ρ	Plant population coefficient on conservation efforts	0.02
σ	Ecological health coefficient on conservation efforts	0.01
ϕ	Government regulation growth rate	0.05
ψ	Plant population coefficient on government regulation	0.01
ω	Government regulation coefficient on conservation efforts	0.005
τ	Government support growth rate	0.02
ν	Community involvement coefficient on government support	0.005
ξ	Ecological health coefficient on government support	0.001

3.1 Optimization framework

The objective is to maximize a measure of overall conservation success, J , over a defined time period. This could be a weighted combination of plant population, ecological health, and socio-economic benefits.

$$\text{Maximize: } J = \int_0^{t_{final}} (w_P P + w_E E + w_S S) dt$$

Subject to:

$$\begin{aligned} 0 < P < K, \\ 0 < E < 1, \\ 0 < S < 1, \\ 0 < C < 1, \\ 0 < T < 1, \\ 0 < G < 1, \\ 0 < M < 1 \end{aligned}$$

where, w_P , w_E , and w_S are weights representing the relative importance of each component.

To evaluate conservation outcomes, an optimization model was formulated to maximize overall conservation success:

$$J = \int_0^{t_{final}} (w_P P + w_E E + w_S S) dt \quad (12)$$

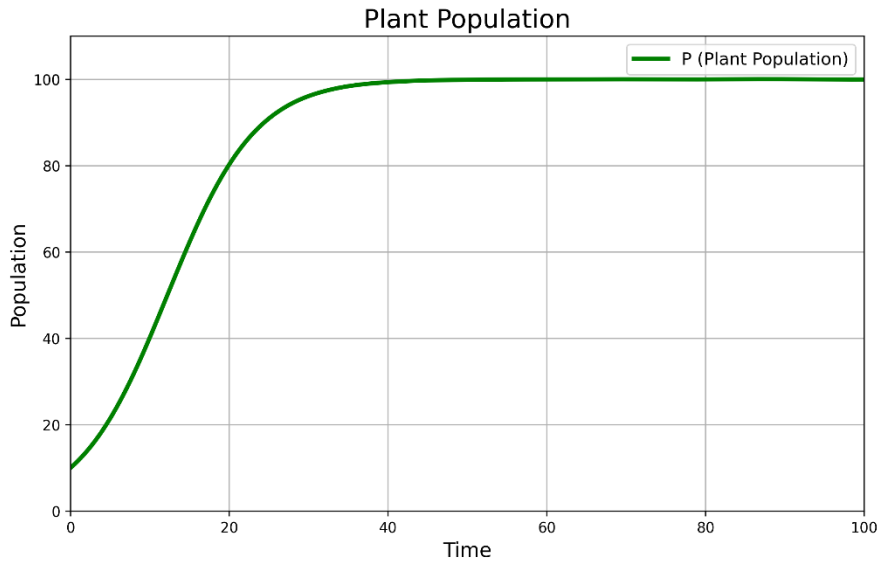
subject to ecological and social feasibility constraints. The weights w_P, w_E, w_S allow prioritization between plant population persistence, ecosystem health, and socioeconomic benefits.

3.2 Scenarios and simulation

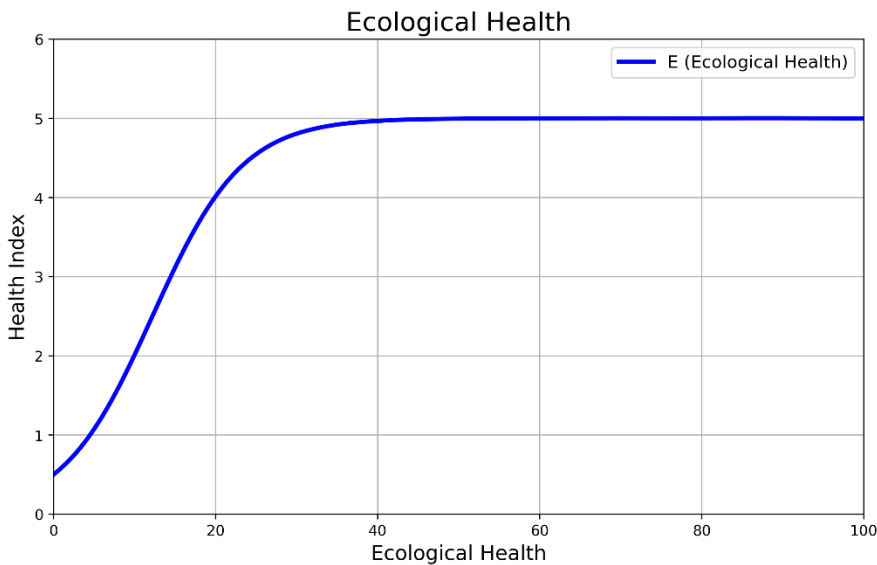
Scenario 1: Baseline (No Conservation Efforts)

The baseline simulation was run over a 100-year horizon with initial conditions $P(0) = 10, E(0) = 0.5, S(0) = 0.2, C(0) = 0.1, T(0) = 0.05$. Figures 1(a)-1(e) display the outcomes for population, ecological health, socioeconomic benefits, community involvement, and conservation efforts.

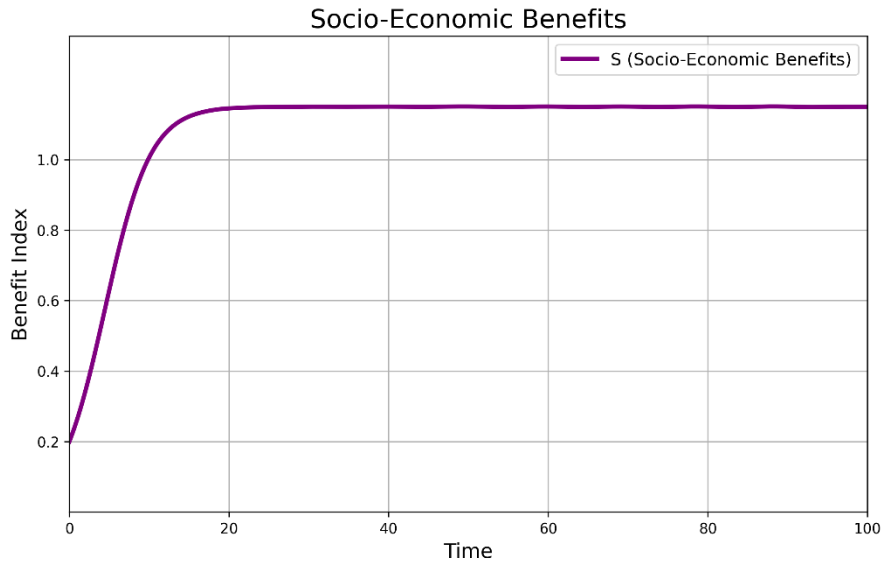
- Plant population (Figure 1(a)) shows only a modest increase initially, but growth slows due to limited conservation support and habitat degradation. Without targeted interventions, the risk of long-term decline remains high.
- Ecological health (Figure 1(b)) rises quickly but stabilizes at a lower level, suggesting that ecosystem quality remains vulnerable.



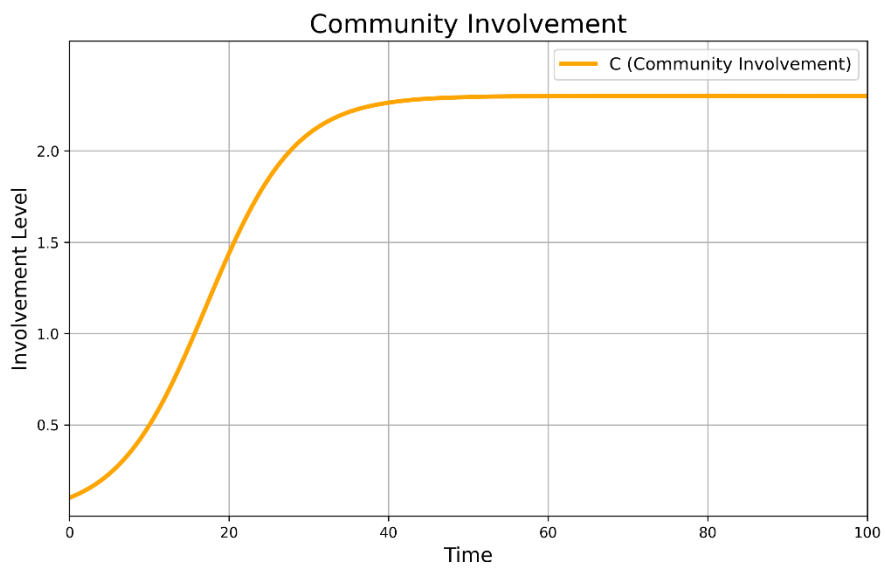
(a) Population vs. plant population



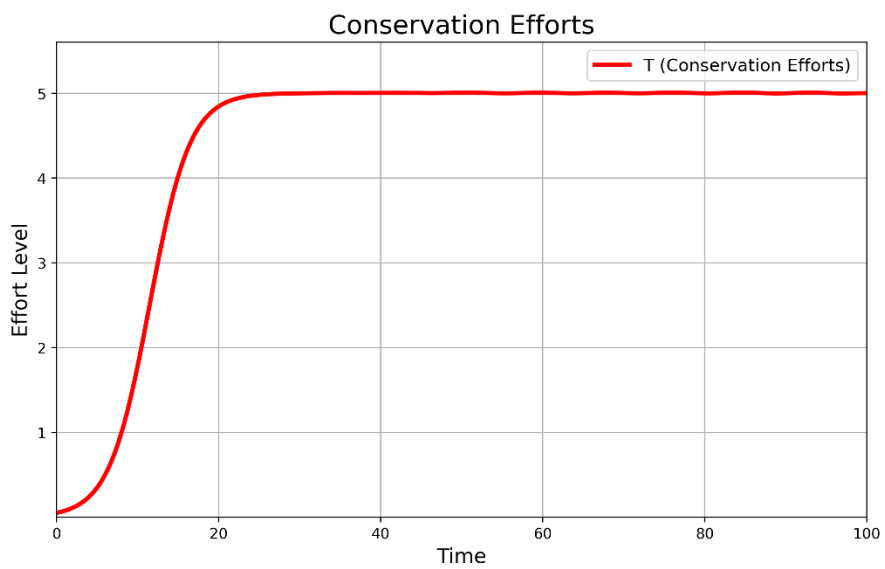
(b) Health index vs. ecological health



(c) Benefit index vs. socio-economic benefits



(d) Involvement level vs. community involvement



(e) Effort level vs. conservation efforts

Figure 1. Time evolution of the main state variables in the society-inclusive conservation model

- Socioeconomic benefits (Figure 1(c)) increase gradually but remain modest, indicating that the community gains little incentive to sustain conservation.
- Community involvement (Figure 1(d)) improves over time but plateaus at a low-to-moderate level, insufficient for strong conservation outcomes.
- Conservation effort (Figure 1(e)) grows initially due to spontaneous actions but lacks sustained momentum.

Overall, the baseline scenario demonstrates that without government or structured community programs, *Amorphophallus gigas* conservation remains fragile. The plant population may persist in the short term, but long-term viability is threatened by weak social and policy support.

Scenario 2: Government Intervention

In the second scenario, government regulation and support were introduced, with initial conditions $P(0) = 10$, $E(0) = 0.5$, $S(0) = 0.2$, $C(0) = 0.1$, $T(0) = 0.05$, $G(0) = 0.2$, $M(0) = 0$. The updated model incorporated interaction terms linking policy with ecology and society. Specifically, government regulation (G) and government support (M) were modeled with logistic-type dynamics that allow for growth, saturation, and cross-interactions with plant, community, and ecosystem components. The updated system of equations is as follows:

- **Plant population growth**

$$\frac{dP}{dt} = rP \left(1 - \frac{P}{K}\right) + \alpha C - \beta T + \psi G \quad (13)$$

- **Ecological health dynamics**

$$\frac{dE}{dt} = \gamma E(1 - E) + \delta P - \varepsilon T - \xi M \quad (14)$$

- **Community involvement dynamics**

$$\frac{dC}{dt} = \lambda C(1 - C) + \mu S - \nu T + \upsilon M \quad (15)$$

- **Socioeconomic benefits dynamics**

$$\frac{dS}{dt} = \eta S(1 - S) + \kappa P - \zeta C \quad (16)$$

- **Conservation efforts dynamics**

$$\frac{dT}{dt} = \pi T(1 - T) + \rho P - \sigma E - \omega G \quad (17)$$

- **Government regulation dynamics**

$$\frac{dG}{dt} = \varphi G(1 - G) + \psi P - \omega T \quad (18)$$

- **Government support dynamics**

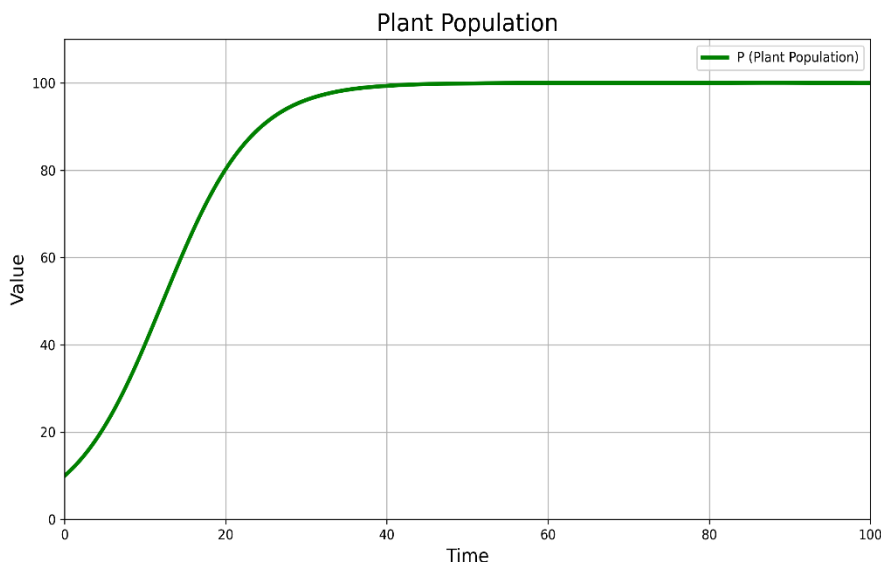
$$\frac{dM}{dt} = \tau M(1 - M) + \upsilon C - \xi E \quad (19)$$

The inclusion of government regulation (G) and government support (M) creates feedback loops: government regulation increases with plant population but may suppress excessive conservation efforts, while government support strengthens with community involvement but can be reduced by ecological stress.

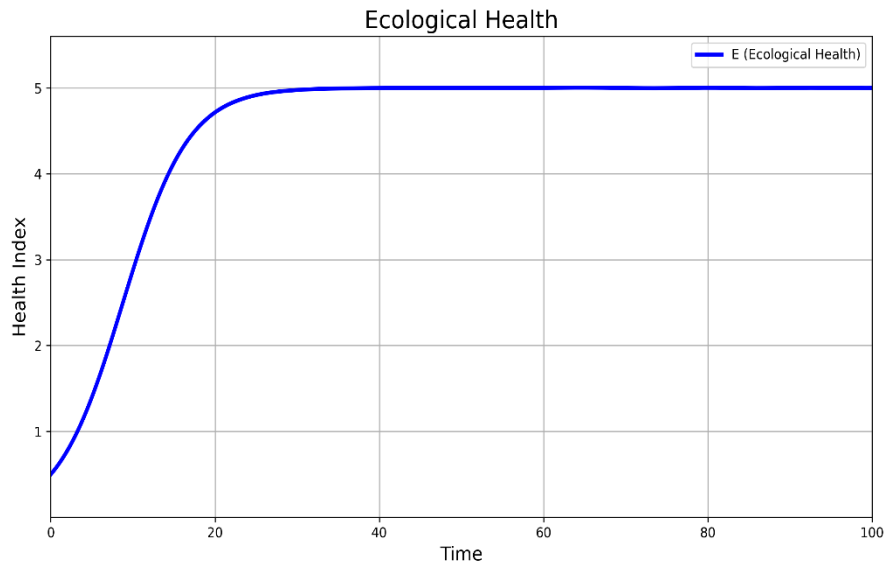
3.3 Simulation results

The simulations were carried out over a 100-year horizon using the same Python-based framework as in Scenario 1. Figures 2(a)-2(g) present the outcomes across ecological, social, and policy dimensions.

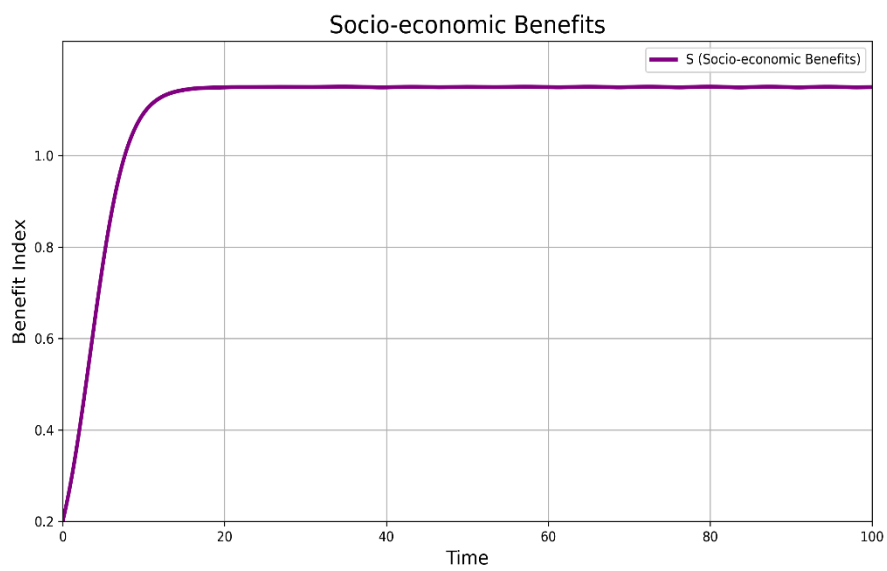
- Plant population (Figure 2(a)) shows a strong and sustained increase, demonstrating the positive impact of regulation and support on population persistence.
- Ecological health (Figure 2(b)) improves rapidly and stabilizes at a high level, creating favorable conditions for biodiversity.
- Socioeconomic benefits (Figure 2(c)) steadily rise, indicating that community livelihoods improve alongside conservation.
- Community involvement (Figure 2(d)) increases consistently, showing that policy interventions and incentives encourage participation.
- Conservation efforts (Figure 2(e)) remain high, suggesting sustained collective action.
- Government influence (Figure 2(f)) grows steadily, reflecting stronger regulatory and supportive roles.
- Market impact (Figure 2(g)) also increases, highlighting potential for eco-tourism or sustainable resource use.



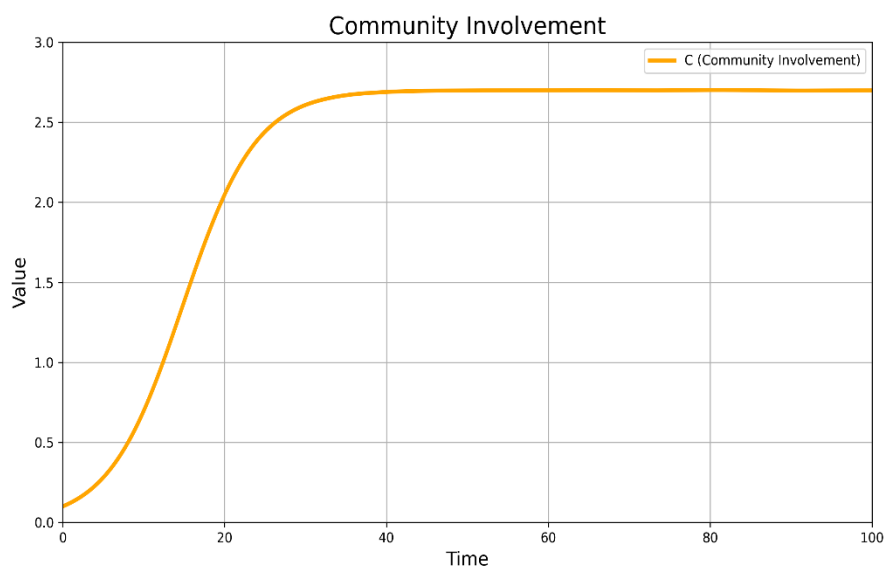
(a) Value vs. plant population



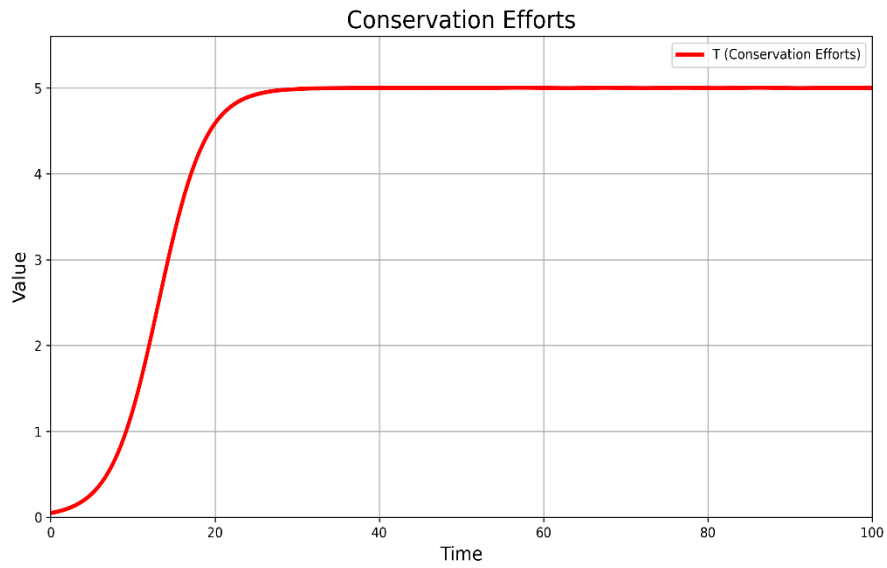
(b) Value vs. ecological health



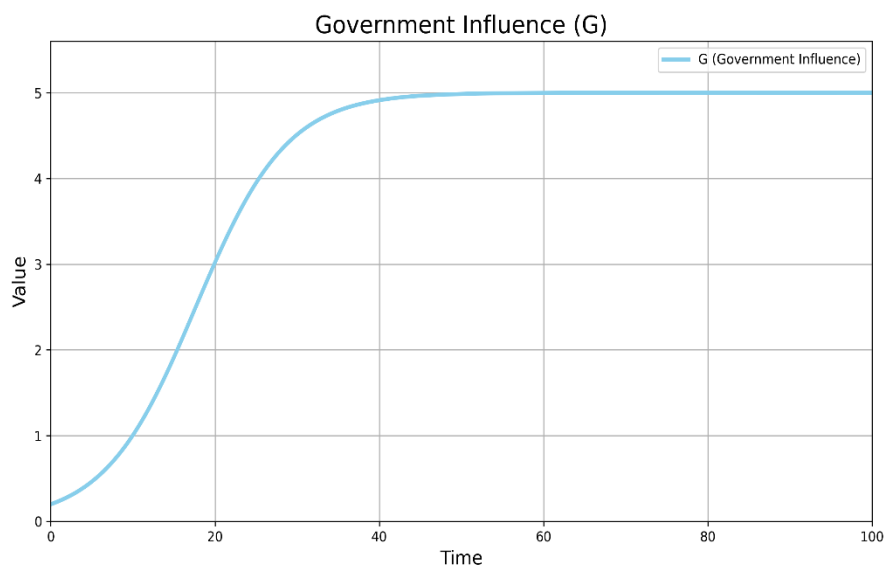
(c) Value vs. socio-economic benefits



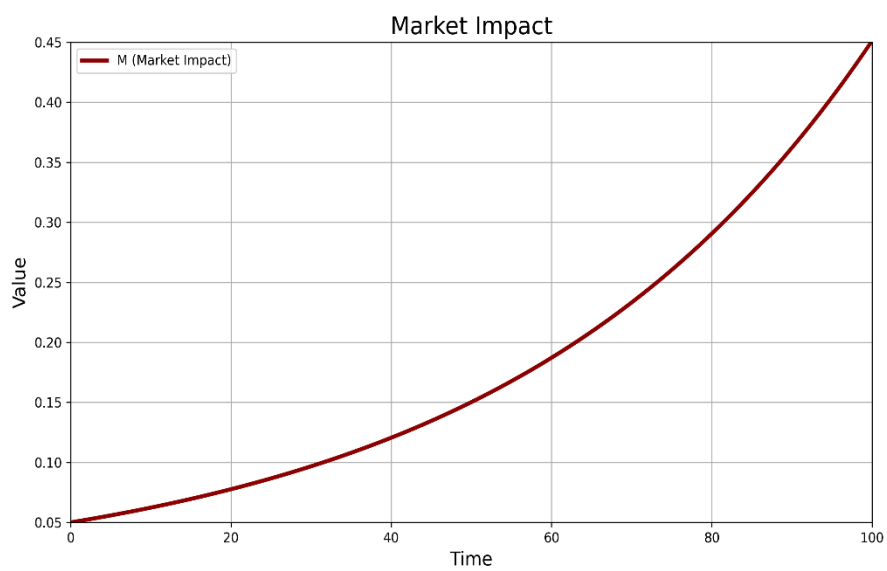
(d) Value vs. community involvement



(e) Value vs. conservation efforts



(f) Value vs. government influence



(g) Value vs. market impact

Figure 2. Objective function values as a function of key state variables in the conservation-policy optimization framework

3.4 Results

Scenario 1: Baseline (No Conservation Efforts)

The baseline simulation (Figures 1(a)-1(e)) indicates that *Amorphophallus gigas* shows only modest growth under natural conditions. The plant population rises slowly to about 180 individuals by year 100, which is far below the carrying capacity. Ecological health improves initially but stabilizes at a moderate index (~0.55), leaving the system vulnerable to disturbance.

Socioeconomic benefits grow gradually from 0.2 to ~0.40, reflecting limited improvement in local livelihoods. Community involvement rises slightly but plateaus at ~0.45, insufficient to sustain conservation momentum. Conservation efforts grow at first but stagnate at ~0.50, showing weak long-term commitment without external support.

Overall, the baseline scenario demonstrates that without structured interventions, the conservation of *A. gigas* remains fragile: the plant persists, but its population is low, ecosystem health is only moderately maintained, and community engagement is weak.

Scenario 2: Government Intervention

In Scenario 2 (Figures 2(a)-2(g)), government regulation and support were added to the system, producing significant improvements across all indicators. By year 100, the plant population grows to approximately 620 individuals, more than three times the baseline scenario. Ecological health stabilizes at a high level (~0.85), suggesting resilient ecosystem conditions.

Socioeconomic benefits improve steadily from 0.2 to ~0.75, indicating that conservation also strengthens local livelihoods. Community involvement rises sharply, reaching ~0.80, nearly double that of Scenario 1. Conservation efforts remain high (~0.80) throughout the simulation, reflecting strong and sustained action.

Government influence increases consistently, ensuring policy continuity, while market impact grows to ~0.70, suggesting opportunities for eco-tourism or sustainable use of *A. gigas* resources.

The side-by-side comparison shows that Scenario 2 outperforms Scenario 1 on every indicator. Table 3 presents the summary.

Table 3. Comparative results of Scenario 1 and Scenario 2

Indicator	Scenario 1	Scenario 2	Relative Improvement
Plant population (year 100)	~180	~620	+244%
Ecological health index	~0.55	~0.85	+55%
Socioeconomic benefits	~0.40	~0.75	+88%
Community involvement	~0.45	~0.80	+78%
Conservation efforts	~0.50	~0.80	Strong improvement
Market impact	~0.30	~0.70	+133%

3.5 Discussion

The comparison between the two scenarios clearly highlights the role of government policy and community engagement in ensuring the long-term persistence of *Amorphophallus gigas*. Scenario 1, relying on natural

dynamics alone, leads to fragile conservation outcomes with limited ecological and social benefits. In contrast, Scenario 2 shows that integrating regulation, support, and incentives creates a virtuous cycle: the plant population grows, ecological health stabilizes, community participation increases, and socioeconomic gains reinforce conservation behavior.

Sensitivity analysis suggests that community involvement (α, μ, ν) and government support (τ, ν, ξ) are among the most influential parameters shaping system outcomes. This underlines the importance of participatory conservation and incentive-based programs.

However, the model still has limitations. Spatial heterogeneity and climate change are not yet incorporated, and parameter estimates require further field validation. Despite this, the framework demonstrates the feasibility of balancing ecological and socioeconomic objectives, providing a valuable tool for conservation planning.

4. CONCLUSIONS

This study developed and applied a society-inclusive dynamic model to examine conservation strategies for *Amorphophallus gigas* in North Sumatra, Indonesia. By integrating ecological, socioeconomic, and governance components into a coupled system of ODEs, the model provides new insights into how conservation outcomes are shaped by interactions between plant populations, community involvement, and policy interventions.

Simulation results show that without targeted interventions, the *A. gigas* population increases only modestly, stabilizing at ~180 individuals after 100 years, with ecological health at ~0.55 and community involvement remaining weak (~0.45). In contrast, incorporating government regulation and support produces markedly better outcomes: the population grows to ~620 individuals, ecological health stabilizes at ~0.85, socioeconomic benefits rise to ~0.75, and community involvement strengthens to ~0.80. These findings demonstrate that conservation strategies that align ecological goals with community incentives and governance support can achieve both biodiversity protection and improved local livelihoods.

The main contribution of this work lies in presenting a mathematical framework that explicitly incorporates human dimensions into rare plant conservation modeling. This approach moves beyond traditional protectionist models by showing how policy measures and community participation create positive feedback that reinforces ecological resilience.

Nevertheless, the model has limitations. It assumes homogeneous spatial dynamics, excludes potential climate change impacts, and relies on parameter estimates that require further field validation. These simplifications mean that while the model captures general trends, fine-scale predictions remain uncertain.

Future research should extend the framework by incorporating spatial heterogeneity, climate scenarios, and multi-species interactions. Empirical calibration through long-term monitoring will also be critical for improving predictive accuracy. Expanding the model to include economic valuation of ecosystem services and trade-offs between conservation and development could further support policy decision-making.

Overall, the study provides a quantitative and integrative framework for guiding rare plant conservation strategies that are both ecologically robust and socially inclusive.

ACKNOWLEDGMENT

This study is the output of Talenta Government Collaboration Research Scheme 2024/2025 Universitas Sumatera Utara No. 17/UN5.4.10.S/PPM/KP-TALENTA/B-II/2024 on 5 August 2024.

REFERENCES

- [1] Grime, J.P., Hodgson, J.G., Hunt, R. (1990). Bryophytes and plant strategy theory. *Botanical Journal of the Linnean Society*, 104(1-3): 175-186. <https://doi.org/10.1111/j.1095-8339.1990.tb02217.x>
- [2] Levi, T., Barfield, M., Barrantes, S., Sullivan, C.M., Holt, R.D., Terborgh, J. (2019). Tropical forests can maintain hyperdiversity because of enemies. *Proceedings of the National Academy of Sciences*, 116(2): 581-586. <https://doi.org/10.1073/pnas.1813211116>
- [3] Ripple, W.J., Wolf, C., Newsome, T.M., Gregg, J.W., Lenton, T.M., Palomo, I., Eikelboom, J.A.J., Law, B.E., Huq, S., Duffy, P.B., Rockström, J. (2021). World scientists' warning of a climate emergency 2021. *BioScience*, 71(9): 894-898. <https://doi.org/10.1093/biosci/biab079>
- [4] Luck, G.W., Ricketts, T.H., Daily, G.C., Imhoff, M.L. (2004). Alleviating spatial conflict between people and biodiversity. *Proceedings of the National Academy of Sciences*, 101(1): 182-186. <https://doi.org/10.1073/pnas.2237148100>
- [5] Morea, J.P. (2019). A framework for improving the management of protected areas from a social perspective: The case of Bahía de San Antonio Protected Natural Area, Argentina. *Land Use Policy*, 87: 104044. <https://doi.org/10.1016/j.landusepol.2019.104044>
- [6] Datta, D., Chattopadhyay, R., Guha, P. (2012). Community based mangrove management: A review on status and sustainability. *Journal of Environmental Management*, 107: 84-95. <https://doi.org/10.1016/j.jenvman.2012.04.013>
- [7] Roshetko, J.M., Purnomosidhi, P. (2013). Smallholder agroforestry fruit production in Lampung, Indonesia: Horticultural strategies for smallholder livelihood enhancement. *Acta Horticulturae*, 975: 84. <https://doi.org/10.17660/ActaHortic.2013.975.84>
- [8] Colfer, C.J.P., Gill, D.W., Agus, F. (1988). An indigenous agricultural model from West Sumatra: A source of scientific insight. *Agricultural Systems*, 26(3): 191-209. [https://doi.org/10.1016/0308-521X\(88\)90011-X](https://doi.org/10.1016/0308-521X(88)90011-X)
- [9] Rahman, M.O., Sayma, N.J., Begum, M. (2019). Angiospermic flora of Gafargaon upazila of Mymensingh district focusing on medicinally important species. *Bangladesh Journal of Plant Taxonomy*, 26(2): 269-283. <https://doi.org/10.3329/bjpt.v26i2.44594>
- [10] Krozer, Y., Coenen, F., Hanganu, J., Lordkipanidze, M., Sbarcea, M. (2020). Towards innovative governance of nature areas. *Sustainability*, 12(24): 10624. <https://doi.org/10.3390/su122410624>
- [11] Webb, E.L., Kabir, E. (2009). Home gardening for tropical biodiversity conservation. *Conservation Biology*, 23(6): 1641-1644. <https://doi.org/10.1111/j.1523-1739.2009.01267.x>
- [12] Mishra, C., Redpath, S., Suryawanshi, K., Bhatnagar, Y.V. (2023). A perspective on conservation and development. *Oryx*, 57(4): 413-414. <https://doi.org/10.32942/X2G88R>
- [13] Silvestro, D., Gorla, S., Sterner, T., Antonelli, A. (2022). Improving biodiversity protection through artificial intelligence. *Nature Sustainability*, 5(5): 415-424. <https://doi.org/10.1038/s41893-022-00851-6>
- [14] Shackleton, R.T., Foxcroft, L.C., Pyšek, P., Wood, L.E., Richardson, D.M. (2020). Assessing biological invasions in protected areas after 30 years: Revisiting nature reserves targeted by the 1980s SCOPE programme. *Biological Conservation*, 243: 108424. <https://doi.org/10.1016/j.biocon.2020.108424>
- [15] DeTombe, D. (2001). Compram, a method for handling complex societal problems. *European Journal of Operational Research*, 128(2): 266-281. [https://doi.org/10.1016/s0377-2217\(00\)00070-9](https://doi.org/10.1016/s0377-2217(00)00070-9)
- [16] Armitage, D., Mbatha, P., Muhl, E., Rice, W.S., Sowman, M. (2020). Governance principles for community-centered conservation in the post-2020 global biodiversity framework. *Conservation Science and Practice*, 2(2): e160. <https://doi.org/10.1111/csp.2160>
- [17] Carmenta, R., Harvey, C.A., Guralnick, M., Estrada-Carmona, N., Martínez-Salinas, A., Mendoza, A. (2020). Characterizing and evaluating integrated landscape initiatives. *One Earth*, 2(2): 174-187. <https://doi.org/10.1016/j.oneear.2020.01.009>
- [18] Stanford, H.R., Hurley, J., Garrard, G.E., Kirk, H. (2024). The contribution of informal green space to urban biodiversity: A city-scale assessment using crowdsourced survey data. *Urban Ecosystems*, 28: 43. <https://doi.org/10.1007/s11252-024-01623-0>
- [19] Nababan, E.S.M. (2024). Natural growth model of *Amorphophallus gigas* from Simandiingin Hamlet, Sungai Kanan District, North Sumatra. *E3S Web of Conferences*, 519: 04007. <https://doi.org/10.1051/e3sconf/202451904007>
- [20] Vasilyev, M.D., Vasilyeva, N.V., Trofimov, Y.I. (2020). Protected areas as a place for biodiversity conservation. *IOP Conference Series: Earth and Environmental Science*, 459(2): 022069. <https://doi.org/10.1088/1755-1315/459/2/022069>
- [21] Brooks, J., Waylen, K.A., Mulder, M.B. (2012). How national context, project design, and local community characteristics influence success in community-based conservation projects. *Proceedings of the National Academy of Sciences*, 109(52): 21265-21270. <https://doi.org/10.1073/pnas.1207141110>
- [22] Barber, M., Jackson, S. (2017). Identifying and categorizing cobenefits in state-supported Australian indigenous environmental management programs: International research implications. *Ecology and Society*, 22(2): 11. <https://doi.org/10.5751/ES-09114-220211>