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Stability analysis of land use change dynamic system in highland area development

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ABSTRACT

The disruption of ecological balance is the most significant challenge to sustainable development in highland areas. In particular, the downstream region is highly vulnerable to hydrometeorological disasters. Therefore, this study aimed to develop the dynamic system capable of simulating land use change to assess the environmental impacts of development activities. The system was constructed in the form of a first-order linear differential equation model based on a land class conversion compartment scheme. Additionally, the dynamic system had more than one equilibrium point, and its stability depended on the eigenvalue. The simulation results from the parameter change showed that ecological stability occurred when the conversion rate of dry land to forest was not equal to zero. This outcome suggested that reforestation was a key effort in managing sustainable highland areas. Mathematically, dynamic system modelling can be used as a new approach to study land use changes in regional development activities.

Keywords: Eigenvalue, equilibrium, hydrometeorology, sustainable development, reforestation

INTRODUCTION

Land class conversion is dominating activities in the management of highland areas, such as agropolitan with the potential to disrupt the balance of ecological system. The desire to improve community welfare leads to hydrometeorological disasters. Agropolitan areas located in the highlands are prone to landslides and soil erosion (Razali et al., 2018) due to the degradation of ecological system. The natural function of trees to maintain soil and water resilience can be disrupted as a result of changes in area of land classes followed by changes in land cover (Sun et al., 2016). Rural areas are directly affected when a hydrometeorological disaster occurs (Dhungana et al., 2023), hence requiring environmental protection.

Changes in agricultural land use, food security, and the capability of an agroecosystem are affected by climate change (Barbier & Hochard, 2016; Karlsson et al., 2016; Wesseh & Lin, 2017). The Agroecosystem areas in highlands are very sensitive to climate change (Taye, 2021). Economic and social demands with increasing population affect land use changes (Kim et al., 2002), which has the potential to increase deforestation (Wang et al., 2015). A balance between environmental protection, economic growth, and the social interests of the community is essential for sustainable development (Fatkhiati et al., 2015; Hardt et al., 2017; Molina, 2016). The participation of communities in sustainable environmental management is good (Barrow, 2006; Li et al., 2017; Nguyen et al., 2016), but appropriate policies are needed (Hitayezu et al., 2017). Proper land use supports food security and environmental sustainability (Hu et al., 2024).

A good mathematical model can describe the working process and predict action (Murray, 2002). Land use change dynamics provide an understanding of ecological stability. Critical transitions represent the dynamics from one stable equilibrium to another, a movement preceded by an asymptotic decrease in stability of the equilibrium from which the movement occurs (Chen et al., 2019, 2024). Stability of equilibrium in a complex ecosystem with a trophic structure is destabilized by spatial spread (Baron & Galla., 2020). Anthropogenic landscape conversion can change ecological dynamics, which has implications for hydrological balance (Endalemaw et al., 2025).

Forest and rural ecosystems play a greater role in the implementation of sustainable development goals (SDGs) in many countries. Therefore, human activities in land use need to be regulated to reduce negative impacts on environment (Cotter et al., 2014; Paulikas et al., 2013). Hydrometeorological disasters in agropolitan areas show that environmental carrying capacity has been exceeded, triggered by the anthropogenic conversion of land classes. Agropolitan areas are ecological systems that cannot avoid continuous disturbances (Islem & Maatoug, 2018; Suleiman et al., 2017).

Population dynamics are very important to understand for ecosystem resilience, and to direct conservation efforts and sustainable management (Pal et al., 2025), as emphasized in SDGs number 15 (United Nations, 2025).

Response to disturbance is characterized qualitatively by stability (Neubert & Caswell, 1997). Understanding the dynamics of ecological systems with different environmental variability is important to predict change behavior and ensure ecosystem sustainability. Therefore, this research aims to analyze stability of ecological systems through modeling the dynamics of land class conversion. The novelty is the mathematical model of dynamic systems used to analyze ecological stability based on characteristic values analytically and empirically simulated. The results are expected to be a serious concern in the preparation of sustainable area management strategies as an effort to protect environment in rural areas. This research contains a descriptive analysis of changes in land class area, mathematical modeling of class conversion dynamics, ecological stability analysis based on eigenvalues, and several scenarios of changes. Field observations were carried out from 2022 to 2023 to confirm and verify the changes in land area as well as the impacts on downstream.

MATERIALS AND METHODS

Data Collection and Processing

Table 1 presents the results of processing the five-year land class area data for the period 2000-2020. This is based on area data for each land class included in the Muria agropolitan area, Pati Regency, Indonesia (Pati Regency, 2011). Data from the districts in 2000, 2005, 2010, 2015, and 2020 were collected with land area of the appropriate class. This area was selected to describe the development activities in the highlands, which have an impact on the downstream. Agropolitan is a development concept used to build an agricultural-based economy in selected areas (Fatkhiati et al., 2015).

Areas other than the rice field land class are classified into settlements consisting of yards and bushes (S), dry land (L), forests (F), as well as plantations consisting of community forests and gardens (P).

The data in **Table 1** describes the dynamics of changes in land area for each five-year land class. Variations in land area are followed by changes in vegetation cover (Bi et al., 2023). Therefore, this data is appropriate to the objectives of the research. Area of forest land classes in 2015 experienced a drastic reduction due to changes in classification rules.

Mathematical Modeling of Dynamic Systems

Digital image processing methods are often used to identify land use changes (Fatkhiati et al., 2015; Islem & Maatoug, 2018; Mohawesh et al., 2015; Suleiman et al., 2017; Tariq et al., 2021). The mathematical model of the dynamic system of land use change is constructed and applied to analyze ecological stability analytically and empirically. This was carried out at the computational laboratory of the department of mathematics, faculty of science and mathematics, Diponegoro University, Semarang, Indonesia.

Table 1. Area of each land in the period 2000-2020

Land class area (ha)	2000	2005	2010	2015	2020
Settlement (S)	6,823	7,114	7,049	9,270	9,093
Dry land (L)	12,637	12,049	12,049	12,580	11,933
Forest (F)	3,394	3,220	3,220	146	1,035
Plantation (P)	810	1,281	1,346	1,668	1,603
Total	23,664	23,664	23,664	23,664	23,664

The dynamics of land area changes in conversion are explained through a mathematical model in the form of ordinary differential equations. Land area conversion described through a compartment scheme of classes is used to construct the dynamic system model. The compartment system is a mathematical abstraction of a network that models the behavior of a continuous physical system consisting of homogeneous components suitable for the analysis of ecological systems in environmental phenomena (Aytaç, 2022; Coskun, 2019). Subsequently, this model is presented in the form of a matrix equation to obtain a coefficient matrix.

Stability Analysis at Equilibrium Point

The theoretical stability type is based on the eigen values of the coefficient matrix and is used as a guide in empirical simulations for several conversion rate scenarios. Therefore, this simulation aims to show the effects of changes in conversion rates on ecological stability in forest recovery scenarios.

RESULTS AND DISCUSSION

Intrinsic Growth Rate of Each Land Class

The exponential population growth model (Armenteras et al., 2017) is used as a method for area growth model of each land class. Therefore, the dynamics of changes in land area can be modeled by a first-order linear ordinary differential equation, namely.

$$dA(t)/dt = rA(t), \tag{1}$$

where $A(t)$ is area of land class (ha) at time t (year), and r is its intrinsic growth rate or average birth rate (Bradley, 2000). The value of r is used as a reference in the simulation of land class conversion scenarios. Based on land area data in 2000 and 2020, the calculation results of the intrinsic growth rate r of each land class are $r_F = -0.059, r_L = -0.003, r_P = 0{,}034, r_S = 0.014$

The intrinsic growth rate of land class area r positive shows an increase in settlements and plantations, while negative values reports a decrease in forests and dry land. The magnitude of $r_F = -0.059$ shows deforestation, hence conversion of forest to non-forest vegetation (Khuc et al., 2018) is confirmed in the highland area.

Mathematical Model of Dynamic System of Land Class Conversion

State variables change over time and are susceptible to environmental disturbances. This mathematical model of the dynamic system of land class conversion was constructed to capture and explain the dynamic changes in the management

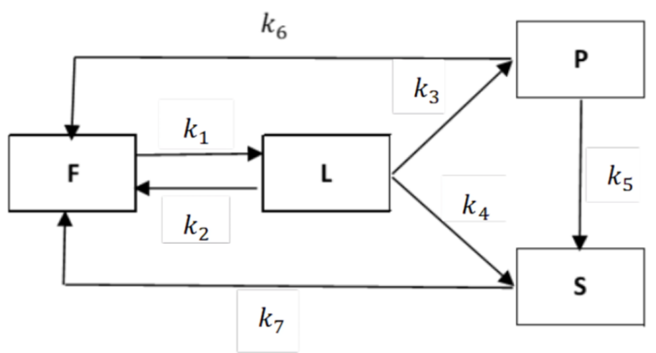

Figure 1. Land class conversion compartment scheme (Source: Authors' own elaboration)

Table 2. Variables and parameters in the model

Variables	N	Unit
Forest land class	F	ha
Dry land class	L	ha
Settlement land class	S	ha
Plantation land class	P	ha
Time	T	Year
Parameters		
Rate of conversion from forest to dry land	k_1	1/year
Rate of conversion from dry land to forest	k_2	1/year
Rate of conversion from dry land to plantations	k_3	1/year
Rate of conversion from dry land to settlements	k_4	1/year
Rate of conversion from plantations to settlements	k_5	1/year
Rate of conversion from plantations to forests	k_6	1/year
Rate of conversion from settlements to forests	k_7	1/year

Note. N: Notation

of agropolitan areas in the highlands. Dynamic system modeling explores system that develops over time when the elements and the relationships are known. This method increases the explicity of the feedback relationships in system (Radosavljevic et al., 2023). Mathematical models are used to describe ecological systems fluctuating around constant state (DeAngelis, 2020; Pal et al., 2025). Therefore, ecological system can be predicted and produce a sustainable management plan by understanding the dynamics of change.

Each land class becomes a state variable in the dynamics model, which is in the form of a first-order linear differential equation system. This model is constructed through a compartment scheme method, as described in **Figure 1**. Field surveys and interviews with the community verify the dynamics of changes in land class area. **Figure 1** explains the FLPS compartment model with a constant land area conversion rate from one land class to another.

Table 2 presents the variables and parameters playing a role in the mathematical modeling of dynamic systems, which correspond to the scheme in **Figure 1**.

This research successfully constructed the dynamic system model of land class conversion based on the compartment scheme in **Figure 1**, as well as variables and parameters in **Table 2**.

$$dF/dt = -k_1F + k_2L + k_6P + k_7S. \tag{2}$$

$$dL/dt = k_1F - (k_2 + k_3 + k_4)L. \tag{3}$$

$$dP/dt = k_3L - (k_5 + k_6)P. \tag{4}$$

$$dS/dt = k_4L + k_5P - k_7S. \tag{5}$$

With initial conditions: F(0) = 3,394 ha, L(0) =12,637 ha, P(0) = 810 ha, S(0) = 6,823 ha , and parameters $k_1, k_2, k_3, k_4, k_5, k_6, k_7 \geq 0$.

The dynamic system model of land class conversion is in the form of a first-order linear differential equation system.

$$\boldsymbol{X}' = \boldsymbol{A}\boldsymbol{X}, \tag{6}$$

where $\boldsymbol{X'} = [F', L', P', S']^T$ and $\boldsymbol{X} = [F, L, P, S]^T$, and $\boldsymbol{A}$ is given in Eq. (7):

$$\boldsymbol{A} = \begin{bmatrix} -k_1 & k_2 & k_6 & k_7 \\ k_1 & -(k_2 + k_3 + k_4) & 0 & 0 \\ 0 & k_3 & -k_5 - k_6 & 0 \\ 0 & k_4 & k_5 & -k_7 \end{bmatrix}. \tag{7}$$

This coefficient matrix $\boldsymbol{A}$ has det ($\boldsymbol{A}$) = 0, hence the center point (origin) $X_0^* = [0, 0, 0, 0]$ is called the degenerate equilibrium point of the linear dynamic system (6) (Freire et al., 2020). The eigenvalues of the matrix $\boldsymbol{A}$ play an important role in determining stability properties of system. Rank ($\boldsymbol{A}$) = 3 shows that there is a non-trivial solution, placing the equilibrium at the center point. The equilibrium points are $\boldsymbol{X}^* = [F^*(t), L^*(t), P^*(t), S^*(t)]$, where:

$$F^*(t) = ((k_2 + k_3 + k_4)(k_5 + k_6)/k_1k_3)\ P(t). \tag{8}$$

$$L^*(t) = ((k_5 + k_6)/k_3)\, P(t). \tag{9}$$

$$P^*(t) = P(t). \tag{10}$$

$$S^*(t) = ((k_4k_5 + k_4k_6 + k_3k_5)/k_3k_7)\, P(t). \tag{11}$$

From Eq. (8), Eq. (9), Eq. (10), and Eq (11), the equilibrium point depends on $P(t)$. Therefore, Eq. (8) and Eq. (9) produce the following relationship:

$$F^*(t) = ((k_2 + k_3 + k_4)/k_1)\ L^*(t). \tag{12}$$

Eq. (8), Eq. (9), and Eq. (10) show that the requirements for the equilibrium point to be defined include $k_1 > 0, k_3 > 0, k_7 > 0$ and $X_0^* = [0, 0, 0, 0]$ occurs when $P(t) = 0$. Effective environmental management of system (Eq. [6]) requires a good understanding of the dynamic properties (Maler, 2000).

Stability Analysis Based on Eigenvalues

Stability analysis is performed to understand the behavior of the dynamic system around the equilibrium point (Pal et al., 2025). The characteristic polynomial of the dynamic system model is given by$|\boldsymbol{A} - \boldsymbol{I}\lambda|$, where:

$$\boldsymbol{A} - \boldsymbol{I}\lambda = \begin{bmatrix} -k_1 - \lambda & k_2 & k_6 & k_7 \\ k_1 & -(k_2 + k_3 + k_4) - \lambda & 0 & 0 \\ 0 & k_3 & -k_5 - k_6 - \lambda & 0 \\ 0 & k_4 & k_5 & -k_7 - \lambda \end{bmatrix}.$$

The characteristic equation is:

Table 3. Some forest restoration scenarios

No	Scenario	Types of stability	Conditions in the 50th year			
			F	L	P	S
1	$k_2 > k_3$	Stable	1,967.2	17,769.5	539.1	3,388.2
2	$k_2 \gg k_3$ & $k_3 \to 0$	Asymptotically stable	2,064.8	18,023.6	187.4	3,388.2
3	$k_2 = k_3$	Asymptotically stable	1,914.4	17,629.8	731.6	3,388.2
4	$k_2 < k_3$	Unstable	1,862.4	17,491.2	922.1	3,388.2
5	$k_2 < k_3$ & $k_2 = 0$	Unstable	1,761.3	17,217.2	1,297.3	3,388.2
6	$k_2 = k_1$	Unstable	10,180.2	9,288.8	806.8	3,388.2
7	$k_2 < k_1$	Stable	7,194.6	12,091.8	989.4	3,388.2
8	$k_2 > k_1$	Unstable	10,619.4	8,877.3	779.1	3,388.2
9	$k_2 < k_1$ & $k_2 = 0$	Unstable	1,761.3	17,217.3	1,297.2	3,388.2
10	$k_2 \ll k_1$ & $k_2 \to 0$	Asymptotically stable	1,776.5	17,202.9	1,296.4	3,388.2

$$|\boldsymbol{A} - \boldsymbol{I}\lambda| = 0. \quad (13)$$

$$(\lambda^3 + c_1\lambda^2 + c_2\lambda + c_4)\,\lambda = 0. \quad (14)$$

where $c_1 = k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7$

$$c_2 = k_1(k_3 + k_4) + (k_1 + k_2 + k_3 + k_4)(k_5 + k_6 + k_7) + k_7(k_5 + k_6)$$

$$c_3 = k_1(k_4k_6 + k_5\,k_7 + k_4k_5 + k_3k_5 + k_3k_7 + k_6k_7) + (k_2 + k_3 + k_4)(k_6\,k_7 + k_5\,k_7)$$

The parameters $k_1, k_2, k_3, k_4, k_5, k_6, k_7$ as well as c_1, c_2, and c_3 also have positive values. According to stability theory (Mattheij & Molenaar, 2002), the characteristic values of the equation (14) consist of:

$$\lambda = 0. \quad (15)$$

Three other characteristic values from the equation (16) namely:

$$\lambda^3 + c_1\lambda^2 + c_2\lambda + c_3 = 0. \quad (16)$$

These three characteristic values have positive or negative real parts determined based on the theorem on the Routh-Hurwitz criterion (Murray, 2002), namely:

$$\Delta_1 = |c_1| = c_1 > 0. \quad (17)$$

$$\Delta_2 = \begin{vmatrix} c_1 & 1 \\ 0 & c_2 \end{vmatrix} = c_1c_2 > 0. \quad (18)$$

$$\Delta_3 = \begin{vmatrix} c_1 & 1 & 0 \\ c_3 & c_2 & 1 \\ 0 & 0 & c_3 \end{vmatrix} = c_3(c_1c_2 - c_3) > 0. \quad (19)$$

Since $\Delta_1 > 0, \Delta_2 > 0$, $\Delta_3 > 0$, the three characteristic values of the equation (16) have negative real parts. Therefore, the equilibrium points of the dynamic model (Eq. [6]) are stable according to stability theory (Mattheij & Molenaar, 2002).

The zero equilibrium point is stable, but the dynamic system is susceptible to disturbances (Olders et al., 2011). The term stability in ecological systems means the tendency to remain close to the initial state or persist when system is subjected to disturbances or environmental changes (DeAngelis & Xu., 2024). Since $\boldsymbol{A}$ is a singular matrix, the dynamic system of land class conversion can have many equilibrium conditions. Therefore, system stability analysis is needed to determine the reaction to small disturbances around the equilibrium conditions.

Model Simulation on Forest Restoration Scenario

Land area of each land class in 2000 was used as the initial condition in the model simulation. Forests are renewable environmental resources with the potential to become extinct (Maler, 2000). Parameters k_1, k_2, k_6, k_7 in the compartment scheme should be taken seriously. Appropriate to the understanding of the intrinsic growth rate as the average growth rate (Bradley, 2000), the value of the parameters is estimated $k_1 \approx 0.059, k_2 + k_3 + k_4 \approx 0.003, k_5 + k_6 \approx 0.034, k_7 \approx 0.014$.

Forest and rural ecosystems play an important role in the implementation of the agropolitan concept (Fatkhiati et al., 2015). Land use conversion poses a threat to forest ecosystems (Shiferaw et al., 2023). Therefore, the simulation of the model (6) is based on the forest recovery scenario. The value of the key parameter k_2 is simulated depending on the value of parameter k_1 or k_3, while conversion to the settlement class is eliminated. This management decision reports $k_2 \geq 0$, $k_4 = 0$, $k_5 = 0$ since $k_3 \approx 0.003$ and $k_6 \approx 0.034$. The model simulation focuses on the role of the parameter values k_1 and k_3 to determine k_2 in identifying the type of stability based on the characteristics of the $\boldsymbol{A}$. Conversion of area of land in the dry land (L) is directed to forest (F) or plantation class (P).

Table 3 shows that the selection of the parameter value scenario $k_2 \geq 0$ depends on $k_1 > 0$ or $k_3 > 0$ to determine the type of stability of the equilibrium point. Variation in dynamic systems causes a transition from stability to instability. This condition is called bifurcation (Li et al., 2022) since there is an unstable equilibrium condition.

Figure 2 illustrates the temporal evolution of land class areas under different forest restoration scenarios over a 400-year period. In scenario 1, the system reaches a stable equilibrium where dry land (L) dominates, while forest (F), plantation (P), and settlement (S) areas diminish to small proportions. Scenario 5 shows an unstable equilibrium characterized by the rapid decline of forests and plantations, with dry land increasingly dominating the landscape. Scenario 6 exhibits an unstable behavior with forest area rapidly increasing beyond its initial state, while dry land and plantation areas shrink, indicating a shift away from agricultural and settlement uses. In contrast, scenario 7

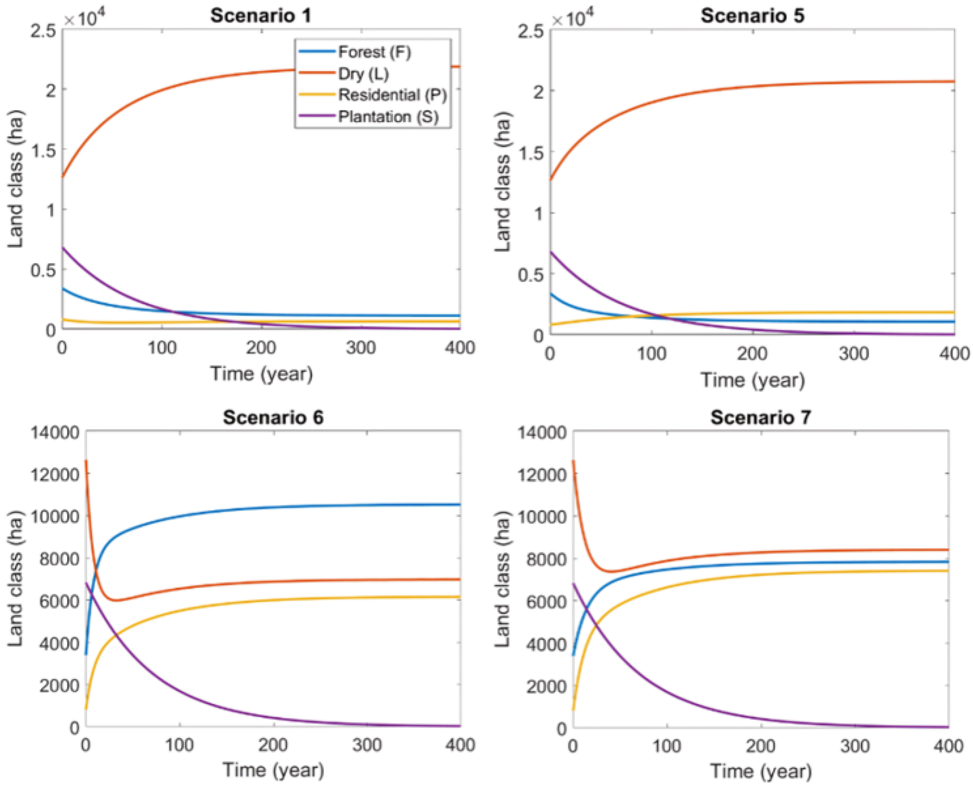

Figure 2. Numerical simulation of system's solution in the case of scenarios 1, 5, 6, and 7 (Source: Authors' own elaboration)

demonstrates a stable configuration with forest and dry land areas reaching a balanced state, while plantation and settlement areas remain limited. These simulations highlight that scenarios with higher conversion rates from dry land to forest tend to produce ecological stability, while insufficient reforestation efforts lead to instability and deforestation.

Figure 3 illustrates the sensitivity of land class dynamics to variations in the key parameter k_2, which represents the rate of conversion from dryland to forest. As k_2 increases, forest area (F) declines at a slower rate and stabilizes at higher levels, indicating enhanced forest retention. Conversely, higher k_2 values lead to reduced dry-land (L) and plantation (P) equilibrium areas, reflecting the trade-off in land allocation. The settlement area (S) remains largely unaffected by changes in k_2, suggesting its dynamics are independent of this particular parameter. These results highlight the critical role of k_2 in reforestation strategy and ecological equilibrium maintenance.

Ecological Stability in the Development of Highland Areas

The analytical ecological analysis method is used to examine stability of system (Chen et al., 2019) through dynamic modelling. The type of equilibrium point stability (Chen et al., 2024) is identified through the existence of eigenvalues from the dynamic system model. The dynamic system model is used to explain stability in ecology, namely the tendency to remain close to the initial state, remain within certain limits, and persist in the face of disturbances or environmental changes (DeAngelis & Xu, 2024). Land class changes that represent variations in cover according to the dynamic system modeling are different from visual maps from GIS (Fatkhiati et al., 2015; Islem & Maatoug, 2018; Mohawesh et al., 2015; Suleiman et al., 2017; Tariq et al., 2021).

Ecological balance paradigm was developed following the principle that the ecosystem is maintained in a state of balance. Environmental goals can be predicted based on the principles of ecological sustainability and resource management with the balance paradigm (Hardy & Patterson, 2012). The selection of values $k_2 \geq 0, k_3 > 0$ is a key parameter in developing a forest restoration strategy to manage sustainable areas. However, the value of $k_2 = 0$ produces the smallest forest area. The parameter value k_2 >0 should be taken seriously in developing a strategy for managing sustainable areas.

Conversion of dryland (L) to forestland class (F) based on system dynamics model with the compartment scheme in **Figure 1** is carried out on the condition that conversion rate k_2 is greater than k_3. The instability of ecological equilibrium can occur when conversion rate k_2 is smaller than k_3. Dryland converted to forest land should be larger than a plantation. Ecological equilibrium in forest and rural ecosystems is important in the implementation of SDGs. Therefore, anthropogenic activities in land use need to be managed to minimize negative impacts on environment (Paulikas et al., 2013).

The development of agropolitan areas on the slopes of Mount Muria, Pati Regency, Indonesia shows deforestation. In this context, serious and urgent efforts are needed in forest restoration to maintain the sustainability of area. Forest restoration requires conversion rate from dry land to forest land. Anthropogenic activities in the highlands trigger hydrometeorological disasters in the downstream or rural areas. According to Wang et al. (2015) and Razali et al. (2018),

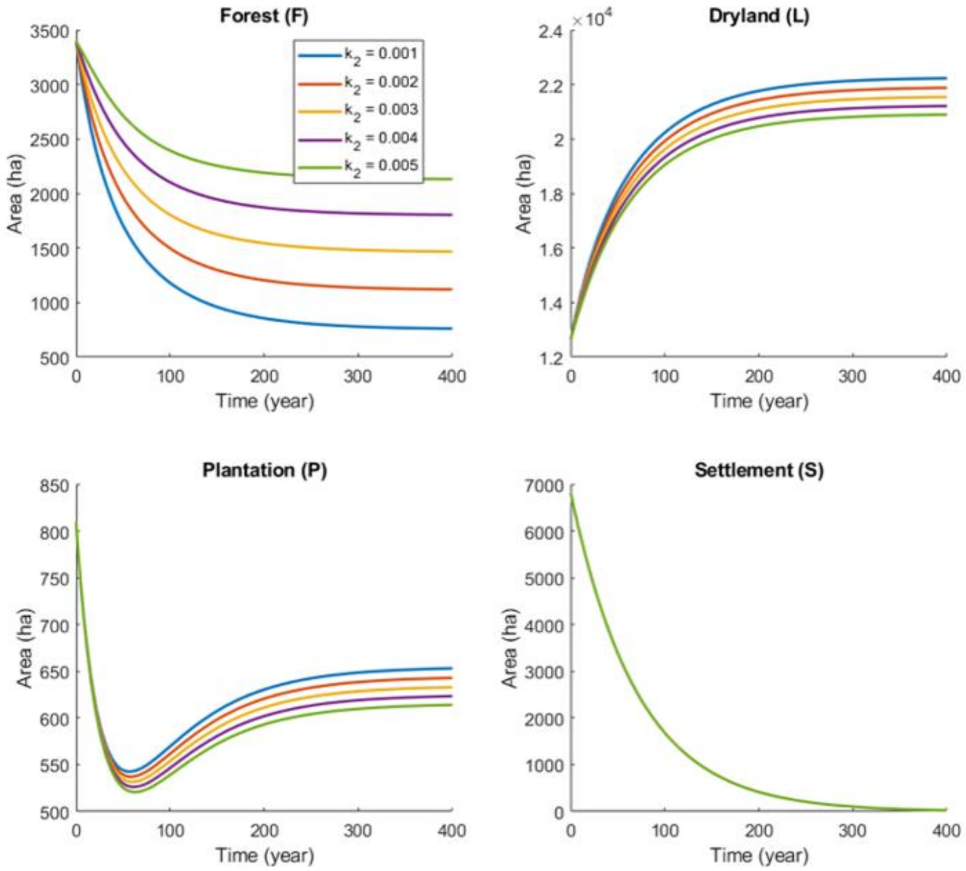

Figure 3. The sensitivity of land class variables under various value of main parameter k_2 (Source: Authors' own elaboration)

widespread deforestation has led to an unstable highland ecosystem. The destruction of natural forests is confirmed by several disasters, such as mud floods, soil erosion, and landslides, disrupting agricultural development.

CONCLUSIONS

In conclusion, ecological stability analysis based on characteristic values of land class conversion dynamic system model provided analytical and numerical information for area management. Controlling the use of natural resources through sustainable management planning considered the balance between economic, social, and environmental interests. Furthermore, environmental development in highland areas was directed at conditions free from floods, landslides, and droughts to protect rural areas. Collective efforts in environmental conservation were important to ensure the sustainability of area to avoid the loss of ecological resources. From the dynamic system model that has been built and the results of analytical and numerical simulations, various parameters have been identified that play an important role in the sustainable management of a highland area. Mathematically, this method can be a solution in studying the behavior of land class conversion dynamics. Finally, the results can be used as a reference for early prevention of environmental damage that can trigger hydrometeorological disasters.

The model provides a quantitative basis for understanding the effects of land class conversion, particularly the importance of forest area preservation. Policymakers can use the simulation outputs to identify thresholds of conversion rates that maintain ecological stability and to formulate strategies that prioritize reforestation and restrict excessive land conversion. While this study focuses on ecological dynamics, the compartment-based modeling approach can be extended to include socio-economic modules. For instance, coupling with economic valuation models or spatial planning tools would enhance decision-making capabilities for integrated sustainable development.

Author contributions: K: conceptualization, formal analysis, investigation, methodology, supervision, validation, writing – original draft, writing – review & editing; **RHSU:** data curation, funding acquisition, investigation, project administration, writing – original draft; **MFA:** data curation, formal analysis, validation, visualization, writing – original draft. All authors agreed with the results and conclusions.

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AI statement: The authors stated that no AI tools were used during the creation of this work.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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