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RESEARCH ARTICLE

Modeling Land Use Change Dynamics in the Buffer Zone of Bukit Rimbang Bukit Baling Wildlife Reserve: A Business-as-Usual Simulation-Based Approach

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Abstract

The buffer zone of the Bukit Rimbang Bukit Baling Wildlife Reserve (BRBB WR) has been experiencing rapid land use changes due to demographic and economic pressures. This study simulated land-use change dynamics using a business-as-usual (BAU) approach to understand land transformation patterns in the absence of policy interventions. A dynamic system modeling approach was employed, with key variables including population growth, expansion of residential areas, and the extension of agriculture and plantations. The analyzed data comprised spatial land cover data from 2008 and 2019 as well as demographic data from 2019 to 2023. The simulation results indicate that without intervention, primary forests and shrublands covering approximately 1.59% and 0.62% of the study area, respectively, in 2019 will disappear before 2028. Meanwhile, secondary forests and bare lands, which occupy 18.65% and 3.83% of the area, respectively, are projected to continue declining until 2035. Conversely, plantations, agricultural land, and settlements have expanded significantly, exacerbating pressure on the ecosystem. Model validation using the Mean Absolute Error (MAE) yielded a value of 0.48%, demonstrating high accuracy in predicting land-use changes. These findings emphasize the urgent need for conservation-based policies to curb deforestation and land conversion, while promoting more sustainable resource management to maintain the ecological and socioeconomic balance in the BRBB WR buffer zone.

Keywords: Buffer zone, land use, simulation model, dynamic system, Business-as-Usual (BAU)

1. Introduction

Forest ecosystems are crucial for sustaining global ecological stability and providing numerous environmental, economic, and social advantages. Forests serve as carbon sinks, regulate climate patterns, conserve biodiversity, and sustain the water cycle, making them indispensable for maintaining environmental stability. However, in recent decades, deforestation driven by agricultural expansion, plantation development, and settlement growth has emerged as a major challenge threatening the sustainability of tropical forests, particularly in Indonesia (Basir, 2025). The rapid conversion of forested areas into productive landscapes has intensified land degradation, biodiversity loss, and climate variability, necessitating urgent conservation intervention.

The buffer zone of the Bukit Rimbang Bukit Baling Wildlife Reserve (BRBB WR) in Kuantan Singingi Regency, Riau Province, is among the regions undergoing major land use changes. This buffer zone serves as a critical ecological corridor, helping to protect the integrity of the BRBB WR core zone, while providing an essential habitat for wildlife species (Rahman and Veriasa, 2017). Its role in maintaining ecological equilibrium is particularly vital as it mitigates external disturbances, prevents habitat fragmentation, and supports the continuity of forest-dependent species.

Analysis of the available data indicates that forested areas within the buffer zone of BRBB WR underwent a significant acceleration of deforestation between 2004 and 2008, with an average annual reduction rate of 19.8% (Harahap, 2017). Most deforested areas have been converted into forest plantations, palm oil plantations, and abandoned lands, reflecting a broader trend of land-use transformation (Suandy et al., 2014).

The primary driver of this rapid land conversion is demographic pressure from population growth in surrounding villages, which has led to the expansion of agriculture, plantation, and residential land (Putera et al., 2019). This pattern is consistent with the global phenomenon of tropical forest degradation, where deforestation not only results in biodiversity loss but also contributes to land degradation, increased soil erosion, and regional climate change (Curtis et al., 2018).

Economic factors have further intensified land conversion rates, particularly due to the rising global demand for plantation commodities, such as palm oil. The increasing economic value of palm oil plantations has incentivized large-scale forest clearance, often at the expense of ecological stability and sustainable land management (Yulian et al., 2017).

The rapid conversion of forests in the BRBB WR buffer zone has also been exacerbated by weak governance of natural resources. Since the reform era, Indonesia's decentralization policy has transferred authority over natural resource management to local governments. However, insufficient oversight, a lack of control over unregulated land conversion, and widespread illegal logging have severely threatened the sustainability of the buffer zone. By 2008, the plantation area in this region had expanded by 159.7% compared to 2004, while the area designated for dryland agriculture had declined at an average rate of 4.2% per year (Suandy et al., 2014). This trend suggests that land use changes are not solely driven by environmental factors but are also influenced by socioeconomic dynamics, shifting livelihood patterns, and economic incentives at the local level.

The extensive land-use changes in the buffer zone of BRBB WR indicate that existing management policies have not been effective in addressing current challenges. Although several policies have been implemented to reduce the deforestation rate, their impact remains limited. Therefore, a model-based approach is required to comprehensively understand land-use dynamics. One such approach is the business-as-usual (BAU) simulation model, which enables the projection of land-use changes under a no-intervention scenario for future years.

The BAU simulation model within the dynamic system modeling framework is a quantitative approach used to depict land-use change dynamics in the buffer zone of the BRBB WR in the absence of policy interventions or significant shifts in ongoing trends. This model serves as an analytical tool for projecting the baseline scenario by simulating key variables that contribute to land use changes based on historical patterns (Murray-Rust et al., 2013). Consequently, this approach provides a deeper understanding of the factors driving deforestation and land conversion.

The BAU simulation model can systematically and data-drivenly map trends in land-use change by integrating critical variables, including population growth, residential expansion, agricultural and plantation land expansion, and the economic dynamics of communities adjacent to the buffer zone (Sterman, 2002; Swanson, 2002). The simulation outcomes from the BAU model offer insights into land transformation under a no-intervention scenario and establish a basis for formulating alternative scenarios that integrate diverse policies or mitigation strategies to alleviate the adverse effects of land-use change (Meyfroidt et al., 2010; Verburg et al., 2013).

The principal benefit of the BAU simulation model is its capacity to assess the efficacy of current policies and discern probable future environmental and social repercussions (Karbasioun et al., 2023). By analyzing long-term land-use change trends, policymakers can develop more sustainable, data-informed, and adaptable management policies for the BRBB WR buffer zone in response to ecological and socioeconomic issues. This method facilitates a systematic examination of land use patterns, thus fostering the creation of more effective mitigation solutions to reduce adverse effects (Wang et al., 2018).

In response to this pressing issue, this study sought to model land-use changes within the buffer zone of BRBB WR by employing the BAU simulation model. The simulation outcomes not only project potential future land transformations in the absence of intervention but also function as a critical analytical tool for evidence-based decision-making. By integrating a data-driven methodology with dynamic system modeling, this approach significantly contributes to the development of science-based policies that uphold ecological equilibrium, while ensuring that development strategies are aligned with the principles of environmental, social, and economic sustainability.

2. Data and Method

2.1 Study Area

This study was conducted in the buffer zone of the Bukit Rimbang Bukit Baling Wildlife Reserve (BRBB WR), which falls under the administrative jurisdiction of the Singingi and Singingi Hilir Districts, Kuantan Singingi Regency, Riau Province. According to Law No. 41 of 1999 on Forestry, a buffer zone is defined as an area situated between cultivation zones and protected areas. However, this regulation does not explicitly specify the extent of the buffer zones, necessitating an interpretation of their spatial coverage based on specific field conditions. In this study, the BRBB WR buffer zone was assumed to encompass the maximum area defined by the outermost boundary points directly adjacent to the surrounding villages. The villages bordering the buffer zone include Pangkalan Indarung, Pulau Padang, Muara Lembu, and Kebun Lado in Singingi District, as well as Petai, Koto Baru, and Sungai Paku in Singingi Hilir District. Based on the administrative boundaries of these villages, the study area was estimated to cover approximately 50,312.23 ha (Figure 1).

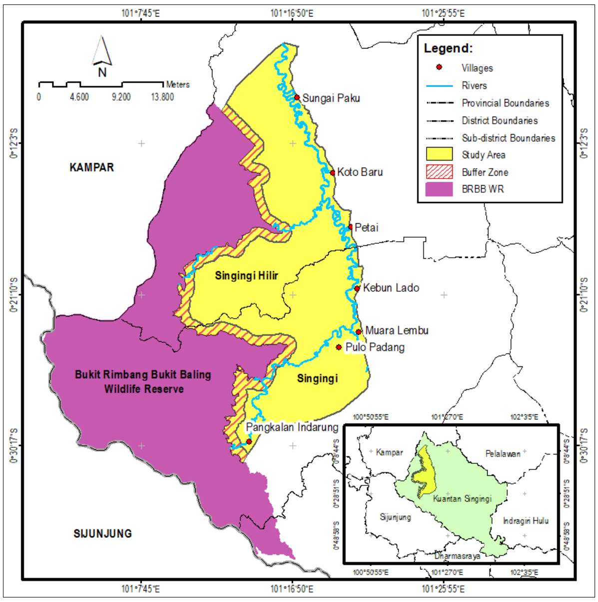

Fig. 1. Administrative map of the study area.

2.2 Data Collection

This study was based on historical data on land-use changes and demographic trends within the study area. Specifically, the demographic data used included population growth rates in the seven villages that serve as the buffer zone of the SM BRBB during the 2019–2023 period. These data were obtained from the Kuantan Singingi Regency in the 2019–2023 report published by the Central Statistics Agency (BPS) of Kuantan Singingi Regency. The full report is publicly accessible through the official website: https://kuansingkab.bps.go.id/id.

Land cover change data in the study area were identified through the analysis of Landsat 8 OLI/TIRS satellite imagery from the 2008 and 2019 recordings, with a spatial resolution of 30 m and a coverage area of 22.43 × 22.43 km. The satellite images were obtained from the United States Geological Survey (USGS) Earth Explorer platform and can be accessed online at http://earthexplorer.usgs.gov. Geometric and atmospheric corrections were performed to eliminate distortions caused by differences in the acquisition angles, atmospheric effects, and lighting variations. These corrections were conducted using ArcGIS Desktop 10.8, version 10.7.0.10450 (Chavez Jr, 1996).

Land cover classification was performed using the Unsupervised Classification method with the Normalized Difference Vegetation Index (NDVI). This method uses the differences in reflectance between the red and near-infrared (NIR) bands in satellite imagery to identify the presence and conditions of vegetation. The NDVI formula is as follows:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad (1)$$

The NDVI values ranged from -1 to +1. Higher NDVI values indicate denser vegetation, whereas lower values correspond to sparser vegetation (Putra et al., 2022).

This study classified NDVI values into nine vegetation density classes, with each class assigned a specific vegetation density weight, as presented in Table 1.

Table 1. Vegetation classification based on NDVI values

NDVI value	NDVI classification	Land cover
0.7 – 0.9	Very dense vegetation, high canopy cover, intact natural ecosystem	Primary Forest
0.6 – 0.8	Dense vegetation, but with some disturbances or natural regeneration	Secondary Forest
0.5 – 0.7	Man-made forest with a regular planting pattern, such as acacia, pine, etc	Forest Plantation
0.4 – 0.7	Medium to high vegetation cover, such as oil palm, rubber, or tea	Plantation
0.2 – 0.5	Cultivated crops, varying by season and growth stage	Agriculture
-0.1 – 0.2	Areas with little to no vegetation, including former mining sites and active extraction zones	Mining
0.0 – 0.3	Buildings, roads, and infrastructure with minimal vegetation, such as urban or rural settlements	Settlement
0.0 – 0.2	Vacant land, dry land, or barren areas with minimal vegetation	Bare land
0.3 – 0.6	Medium vegetation, consisting of shrubs or land undergoing regeneration	Shrubs

2.3 Development of Business-as-Usual (BAU) Model

This study adopted a dynamic system modeling approach through a BAU simulation to analyze land use change dynamics. This method projects future land use transformations based on historical trends in the absence of policy interventions. The BAU simulation model developed in this study integrated several key variables, including population growth, settlement expansion, agriculture, plantations, shrubs/bushes, bare land, and primary and secondary forests. These variables collectively influence landscape dynamics within the BRBB WR buffer zone.

The development of the BAU model follows a structured sequence of steps to ensure precision in dynamic system modeling. These stages include:

1. *Screening and quantification of population data*

   Population data from the study area for the period 2019–2023 were systematically analyzed to determine the annual population growth rate. This process involved screening and quantifying demographic trends over the five-year period, ensuring an accurate estimation of population dynamics within the study area. The annual population growth rate was calculated following the method proposed by (Putri et al., 2020), using the following formula:

   $$r = \left(\frac{P_t - P_0}{P_0}\right) x \frac{100}{t} \qquad (2)$$

   where r = annual population growth rate (%); P_t = population at the end of the study period (2023); P_0 = population at the beginning of the study period (2019); t = number of years (2023 - 2019 = 4).

2. *Quantification and tabulation of spatial data on land cover change*

   Land cover change data were analyzed using ArcGIS Desktop 10.8 (version 10.7.0.10450) by overlaying the 2008 land use map with the 2019 land use map. This process enabled the identification of land use change patterns and provided insights into spatial transformations over time. Additionally, the concentration of land use change was assessed following the method proposed by (Verburg et al., 2004), using the following formula:

   $$R = \frac{A_t - A_0}{t} \qquad (3)$$

   $$R_{\%} = \left(\frac{A_t - A_0}{A_0 x t}\right) x100\% \qquad (4)$$

   $$R_{avg} = \frac{\sum_{i=1}^{n} R_i}{n} \qquad (5)$$

   where R = average land area change per year (ha/year); $R_{\%}$ = average land change per year in percentage (%/year); R_{avg} = average land change per year across nine land cover classes (ha/year); A_0 = land cover area in the initial year of observation (ha); A_t = land cover area in the final year of observation (ha); t = difference in years between At and A_0 (observation period); R_i = land change for the i-th land cover class; n = represents the total number of land cover classes.

3. *Development of a Causal Loop Diagram (CLD)*

   A CLD was constructed to illustrate the interconnections among key system variables (Aditya, 2017), highlighting the relationships between the factors influencing land use change dynamics (Zhao et al., 2016).

4. *Development of a Stock-Flow Diagram (SFD)*

   The SFD provides a graphical representation of system interactions, depicting how stock and flow variables evolve within a dynamic process. In this model, stock represents the accumulation of a variable within the system, whereas flow reflects changes in stock due to inflows and outflows. The SFD incorporates stocks, flows, auxiliary variables, and feedback loops, which can be either reinforced (positive feedback) or balanced (negative feedback) (Verburg et al., 2004).

5. *BAU model simulation*

   The BAU model was simulated to project land use changes in the study area over an 15-year period (2020–2035). The simulation was executed using Powersim Studio 10 Academic (version: 10.14.555.6), facilitating dynamic system-based modeling to visualize future land-use trends.

6. *Model validation*

   The final stage of the study involved model validation to evaluate the accuracy of projections. Validation was conducted using the Mean Absolute Error (MAE) method, which quantifies the deviation between the average simulated values and actual observed data. This approach followed the method proposed by (Hodson, 2022) and was calculated using the following formula:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|S_i - A_i| \qquad (6)$$

where MAE = mean absolute error; n = number of observations; S_i = simulated value for the i-th observation; A_i = actual observed value for the i-th observation. The model was considered valid if the MAE value was below 5% (Harahap, 2017).

3. Results and Discussion

The population in the buffer villages of BRBB WR has experienced a significant increase between 2019 and 2023. The total population has grown from 17,774 in 2019 to 21,360 in 2023, with an average annual growth rate of 2.38%. This increase was particularly notable in the Singingi Hilir District, where the population rose from 8,096 in 2019 to 11,461 in 2023 (Table 2). Population growth within the study area is driven by multiple factors, including birth rates; labor migration to the agricultural, plantation, industrial forest plantation, and mining sectors; and shifting economic patterns that increasingly depend on natural resource exploitation. As the population expands, the demand for land for residential, agricultural, and plantation purposes intensifies. This growing land demand accelerates deforestation and the conversion of natural ecosystems into productive land, which in turn may result in substantial landscape alterations with the potential to disrupt the ecological balance of the region (Sloan et al., 2017).

Table 2. Population growth in BRBB WR buffer zone villages for the period 2019-2023

Villages	Population (person/years)				
	2019	2020	2021	2022	2023
Pangkalan Indarung	1,927	1,769	1,834	1,817	1,961
Pulau Padang	1,106	1,211	1,282	1,335	1,344
Muara Lembu	4,854	4,573	4,549	4,661	4,782
Kebun Lado	1,791	1,808	1,729	1,756	1,812
Petai	2,762	3,448	3,502	3,650	3,851
Koto Baru	3,443	4,363	4,542	4,627	4,887
Sungai Paku	1,891	2,444	2,493	2,670	2,723
Total	17,774	19,616	19,931	20,516	21,360

Population growth is intrinsically connected to land-cover changes within the study area. A comparative analysis of land cover between 2008 and 2019 revealed substantial transformations, particularly a decline in primary forest cover due to increasing human activities. The conversion of land has been primarily driven by the growing demand for residential, agricultural, and plantation areas, along with other sectors dependent on natural resource exploitation. The observed land-cover change trends over the past 11 years suggest mounting pressure on the ecosystem within the study area. A comprehensive summary of these land cover changes is presented in Table 3.

The data presented in Table 3 reveal a substantial decline in primary forest cover by 93.06%, from 11,494.27 ha in 2008 to 797.73 ha in 2019. This extensive deforestation has been primarily driven by the expansion of forestry, plantations, and agricultural activities, leading to a significant reduction in the extent of natural forests. The rapid loss of primary forests is strongly linked to the growth of industrial forest plantations, expansion of palm oil plantations, and widespread land conversion for agricultural purposes (Margono et al., 2014). Conversely, secondary forest cover increased by 83.02%, suggesting that although some areas have retained tree cover, the ecosystem has undergone significant degradation. This trend is largely attributed to illegal logging and unsustainable land conversion practices that have altered the ecological integrity of the region.

Table 3. Land cover change trends in the BRBB WR buffer zone for the period 2008–2019

Land cover	Total area (ha/years)		Land cover change	
	2008	2019	ha	%
Primary forest	11,494.27	797.73	10,696.54	93.06
Secondary forest	5,126.56	9,382.45	4,255.89	83.02
Forest plantation	8,031.32	16,573.68	8,542.36	106.36
Plantation	11,489.08	13,187.58	1,698.50	14.78
Agriculture	-	6,159.09	6,159.09	100.00
Mining	543.72	1,632.89	1,089.17	200.32
Settlement	287.81	330.34	42.53	14.78
Bare land	8,304.43	1,926.59	6,377.84	76.80
Shrubs	4,892.49	314.19	4,578.30	93.58

A significant transformation in land cover within the buffer zone was the expansion of forest plantation, which increased by 106.36%, from 8,031.32 ha in 2008 to 16,573.68 ha in 2019. This shift marks a transition from natural forest ecosystems to monoculture-based production systems, which, while economically beneficial, present substantial environmental concerns. Although the expansion of industrial forest plantations in the BRBB WR buffer zone is in accordance with government-issued permits, it has been widely criticized for contributing to biodiversity loss, disrupting ecosystem equilibrium, and altering the microclimate through the removal of native tree species that serve as essential carbon sinks (Abood et al., 2015).

In addition to the forestry sector, both plantations and agricultural land have exhibited substantial expansion. Plantation areas increased by 14.78%, from 11,489.08 ha in 2008 to 13,187.58 ha in 2019, predominantly driven by the growth of oil palm plantations. Concurrently, the agricultural land area doubled, signifying the extensive conversion of previously non-productive land into farmland. This trend is largely attributable to rising food demand and shifting economic dependencies within local communities toward the agricultural sector. However, in the absence of sustainable management practices, this expansion could intensify environmental pressures, including soil erosion, land degradation, and declining water quality owing to excessive fertilizer and pesticide use (Laurance et al., 2014).

The mining sector also experienced a substantial increase, expanding by 200.32%, from 543.72 ha in 2008 to 1,632.89 ha in 2019. The rapid growth of mining activities has the potential to exacerbate environmental degradation, particularly through deforestation, river sedimentation, and contamination of mining waste. These activities are often linked to irreversible ecosystem damage, especially in conservation areas, which should remain strictly protected from resource exploitation (Sloan et al., 2017).

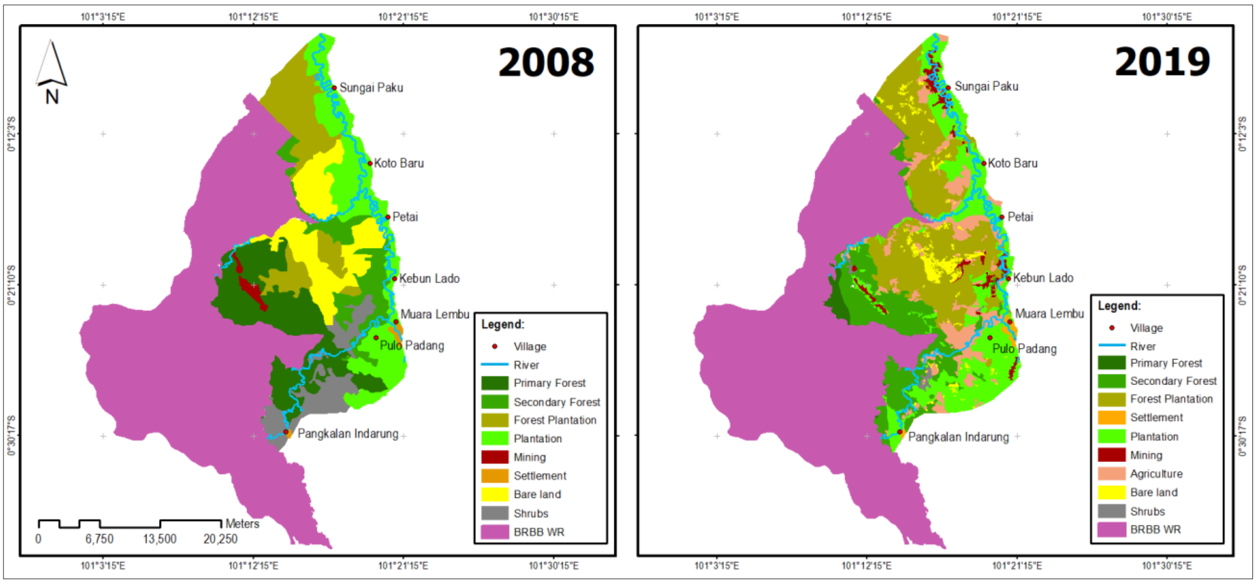

Fig. 2. Land cover change in the BRBB WR buffer zone for the period 2008-2019.

Conversely, the extent of bare land decreased by 76.80%, from 8,304.43 ha to 1,926.59 ha. The conversion of bare land into agricultural fields, plantations, and residential zones presents dual challenges. While it reflects increased land productivity for economic and social purposes, it simultaneously heightens the pressure on already limited land resources, potentially reducing the region's environmental carrying capacity (Adrianto et al., 2020).

In parallel, settlement areas expanded by 14.78%, increasing from 287.81 ha in 2008 to 330.34 ha in 2019. This expansion is closely linked to population growth in buffer villages, further amplifying the demand for land and natural resources. The spread of settlements has contributed to habitat fragmentation, heightened forest exploitation for building materials, and an increased frequency of human-wildlife conflicts, as many species continue to rely on conservation areas for survival (Gunawan et al., 2022). A spatial representation of land cover changes in the BRBB WR buffer zone between 2008 and 2019 is presented in Figure 2.

The observed land cover changes in the BRBB WR buffer zone align with a BAU trajectory, characterized by escalating environmental pressures driven by uncontrolled economic activities. To examine these dynamics in greater depth, this study utilizes a BAU land-use change simulation based on a dynamic modeling approach. The simulation was designed to project future land cover transformations in the absence of policy interventions, offering insights into the long-term consequences of current land-use trends.

In constructing the BAU simulation model, land use change dynamics are represented through a Causal Loop Diagram (CLD), which maps the cause-and-effect relationships among population growth, rising land demand, land conversion, and their influence on land cover changes in the BRBB WR buffer zone. This approach facilitates the identification of dynamic interaction patterns within the system, and serves as a foundation for developing a more precise BAU simulation model. The CLD in this study comprises two primary loop types: reinforcing and balancing, as illustrated in Figure 3.

The reinforcing loop in the diagram highlights population growth as a central driver of increasing land demand, particularly for residential expansion and economic activities, such as agriculture and plantations. As land demand increases, primary and secondary forests undergo deforestation, while open land and shrubs are converted into productive land. This expansion enhances economic output and income, attracts migration and contributes to higher birth rates. As a result, this cycle continuously reinforces itself, accelerating land-use changes within the BRBB WR buffer zone.

Forest plantations and mining activities are excluded from the BAU model loops. This exclusion is based on the premise that these economic activities are subject to government regulation with predetermined land allocations under official permits. Consequently, it was assumed that the spatial extent of these activities remained constant throughout the simulation period.

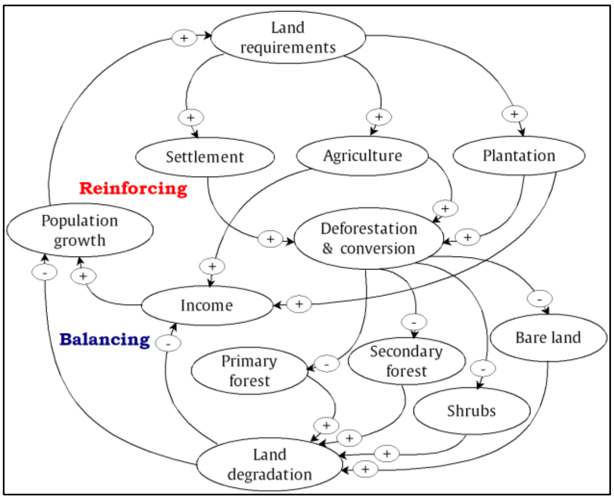

Fig. 3. CLD diagram of the BAU model for land use change in the BRBB WR buffer zone

Conversely, the balancing loop demonstrates how environmental degradation resulting from excessive land exploitation can constrain long-term economic growth. Continuous deforestation and land conversion contribute to the deterioration of soil quality, increasing the likelihood of land degradation. Consequently, agricultural and plantation productivity declines, disrupting household income. If these conditions persist, the environmental carrying capacity necessary to sustain economic activities gradually diminishes, eventually leading to a slowdown in population growth within the BRBB WR buffer zone.

The BAU model simulation was developed using the baseline data from 2008 to 2023. Population projections were estimated based on the average annual population growth rate of 2.38% recorded between 2020 and 2023 in the seven buffer villages of SM BRBB. The number of households (RT) was determined by dividing the total population by the average household size, which consists of four individuals per RT. Additionally, the number of farming households (RTP) was calculated as 37.94% of the total population, divided by the same household size parameter.

Land cover change projections were derived from historical land cover data from 2008 to 2019. The projected increase in settlement areas was calculated using the average land requirement per household (0.028 ha/RT) multiplied by the increase in the number of RTs in the seven buffer villages of the BRBB WR. Similarly, the projected expansions in agricultural and plantation areas were estimated by multiplying the increase in RTPs by the average land requirements for agriculture (1.89 ha/RTP) and plantations (2.95 ha/RTP).

Deforestation and land conversion projections were determined based on the total area of deforested and converted land multiplied by the average annual reduction rates observed for different land cover types between 2008 and 2019. The rates were recorded as follows: primary forest (24.62% per year), secondary forest (9.80% per year), bare land (14.68% per year), and shrubs (10.54% per year).

To systematically represent stock changes over time, differential equations for each projection were structured within a stock flow diagram (SFD). The SFD integrates inputs from causal variables forming feedback loops, illustrating how system dynamics are shaped by interactions among stocks, flows, and auxiliary variables that regulate the system. By employing SFD, stock variations can be systematically analyzed, offering a comprehensive understanding of the key factors driving land-use changes in the BRBB WR buffer zone, as depicted in Figure 4.

The Business-as-Usual (BAU) model simulation for land-use change in the SM BRBB buffer zone was conducted over a 15-year period (2020–2035). The selection of this time frame was informed by several critical factors, including land change cycles, constraints on the accuracy of long-term predictions, policy relevance, socio-economic dynamics, and the availability of historical data, which are generally analyzed within a 10–20-year time frame (Lambin et al., 2003; Sterman, 2002). A 15-year projection is considered a sufficiently representative period for capturing ongoing land-use change trends while minimizing the uncertainties associated with extended forecasting, which are inherently more difficult to predict (Bongaarts, 2009). A graphical representation of the BAU model simulation results illustrating population growth and land-use changes in the BRBB WR buffer zone from 2020 to 2035 is shown in Figure 5.

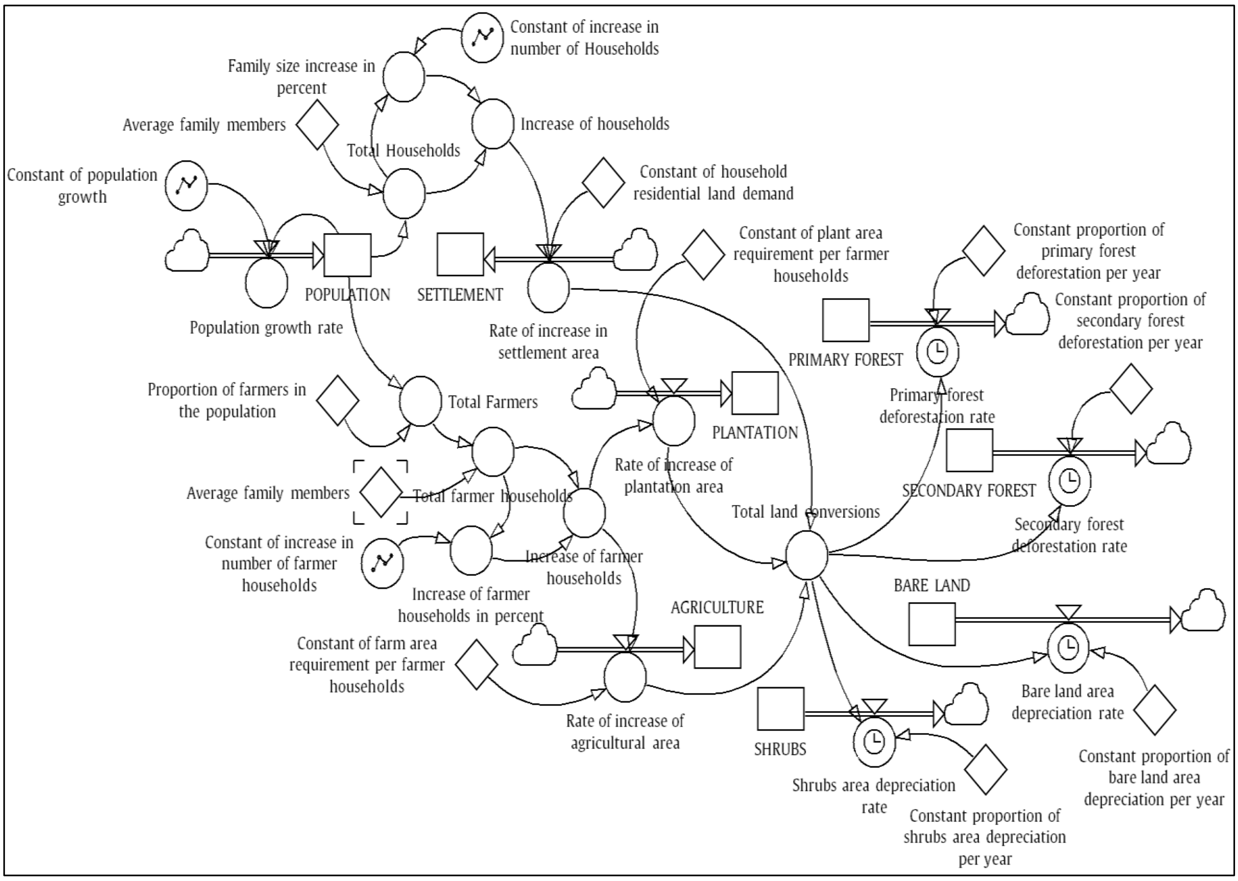

Fig. 4. SFD diagram of the BAU model for land use change in the BRBB WR buffer zone.

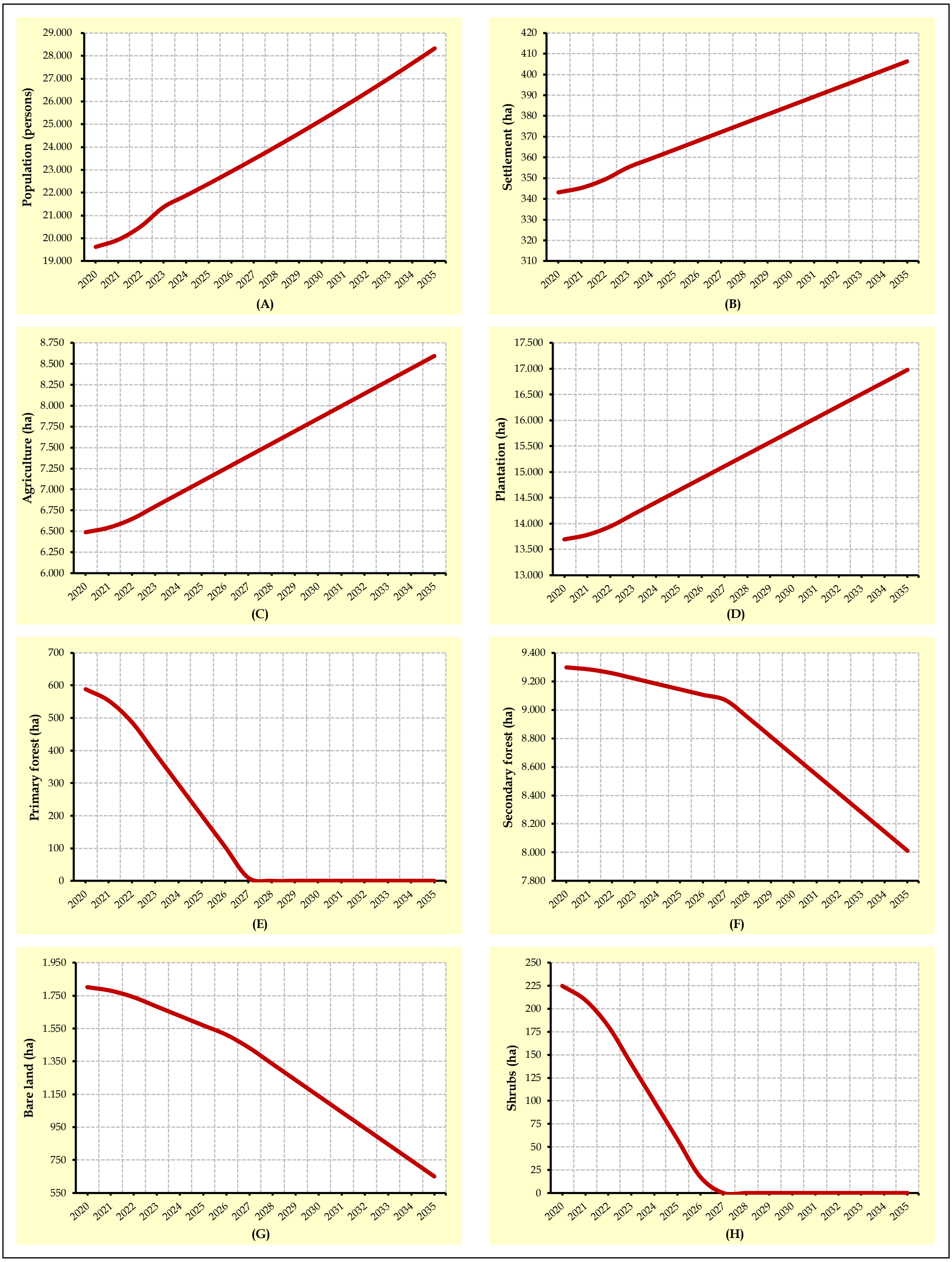

Fig. 5. BAU model simulation projections for the period 2020–2035, illustrating trends in (A) population, (B) settlement, (C) agriculture, (D) plantation, (E) primary forest, (F) secondary forest, (G) bare land, and (H) shrub changes in the BRBB WR buffer zone.

As illustrated in Figure 5, the BAU model simulation results demonstrated a continuous expansion of settlements, agricultural land, and plantations driven by ongoing population growth within the BRBB WR buffer zone. The increasing demand for land allocated for residential, agricultural, and plantation purposes has accelerated deforestation and land conversion, leading to significant reductions in primary forests, secondary forests, bare land, and shrubs. These trends highlight the growing pressure on natural ecosystems, as human activities continue to shape the landscape. A comprehensive projection of population growth and land-use changes within the SM BRBB buffer zone based on the BAU model simulation is provided in Table 4.

Table 4. Trends in population growth and land use change in the buffer zone of BRBB WR based on the BAU model simulation projections for the period 2020–2035

Years	Population (persons)	RT	RTP	Settlement (ha)	Agriculture (ha)	Plantation (ha)	Primary forest (ha)	Secondary forest (ha)	Bare land (ha)	Shrubs (ha)	Total land use changes	
											(ha)	(%)
2020	19,615	4,843	1,837	343.10	6,485.77	13,697.03	588.70	9,299.28	1,801.96	224.72	32,440.56	62.00
2021	19,931	4,920	1,867	345.28	6,541.64	13,784.15	552.96	9,285.06	1,780.64	209.42	32,499.15	62.11
2022	20,517	5,065	1,921	349.33	6,645.39	13,945.94	486.57	9,258.65	1,741.06	181.01	32,607.96	62.32
2023	21,360	5,273	2,000	355.17	6,795.08	14,179.37	390.80	9,220.54	1,683.96	140.02	32,764.93	62.62
2024	21,869	5,399	2,048	359.44	6,944.76	14,412.79	295.41	9,182.59	1,627.08	99.19	32,921.27	62.92
2025	22,389	5,527	2,097	363.71	7,094.45	14,646.22	200.02	9,144.64	1,570.21	58.36	33,077.61	63.22
2026	22,922	5,659	2,147	367.98	7,244.14	14,879.65	104.64	9,106.69	1,513.33	17.53	33,233.95	63.52
2027	23,468	5,794	2,198	372.24	7,393.82	15,113.07	9.25	9,068.73	1,433.16	-	33,390.29	63.82
2028	24,026	5,931	2,250	376.51	7,543.51	15,346.50	-	8,944.65	1,335.46	-	33,546.63	64.11
2029	24,598	6,073	2,304	380.78	7,693.19	15,579.93	-	8,811.31	1,237.76	-	33,702.97	64.41
2030	25,183	6,217	2,359	385.05	7,842.88	15,813.36	-	8,677.97	1,140.06	-	33,859.31	64.71
2031	25,783	6,365	2,415	389.31	7,992.56	16,046.78	-	8,544.63	1,042.36	-	34,015.65	65.01
2032	26,396	6,517	2,472	393.58	8,142.25	16,280.21	-	8,411.29	944.66	-	34,171.99	65.31
2033	27,025	6,672	2,531	397.85	8,291.94	16,513.64	-	8,277.95	846.95	-	34,328.33	65.61
2034	27,668	6,830	2,591	402.12	8,441.62	16,747.06	-	8,144.61	749.25	-	34,484.66	65.91
2035	28,326	6,993	2,653	406.38	8,591.31	16,980.49	-	8,011.27	651.55	-	34,641.00	66.21

The BAU model projections for 2020–2035 indicate a significant increase in total land-use conversion, rising from 32,440.56 ha in 2020 to 34,641.00 ha in 2035, with the percentage of land-use change increasing from 62.00% to 66.21%. These findings highlight the extensive scale of land conversion, particularly affecting primary and secondary forests, which continues to decline owing to the expansion of settlements, agriculture, and plantations.

The projected population growth, from 19,615 people in 2020 to 28,326 people in 2035, further intensifies the pressure on land resources. As the population increases, the number of households (RT) and farming households (RTP) also increases, driving a higher demand for land for settlements, agriculture, and economic activities. These findings are consistent with previous research demonstrating that population growth in the buffer zones of conservation areas contributes to deforestation and ecosystem degradation, primarily through agricultural and residential expansion (Bongaarts, 2009). Other studies have shown that uncontrolled population growth can result in the overexploitation of natural resources, exacerbating environmental degradation and increasing the risk of land conflicts (Seto et al., 2012).

A particularly alarming outcome of the BAU simulation is the complete loss of primary forests by 2027, indicating that without policy interventions, deforestation will reach a critical threshold within less than a decade. Furthermore, secondary forest cover is projected to decline by 1,288.01 ha, shrinking from 9,299.28 ha in 2020 to 8,011.27 ha in 2035. This trend reflects the ongoing transformation of natural ecosystems into fragmented landscapes with serious consequences for biodiversity and ecosystem stability (Hansen et al., 2013). Previous research has shown that rapid deforestation in tropical regions leads to species loss, ecosystem function decline, and increased carbon emissions, contributing to global climate change (Laurance et al., 2014).

The expansion of plantations is projected to be the most significant land use change, increasing from 13,697.03 ha in 2020 to 16,980.49 ha in 2035, a total increase of 3,283.46 ha. This expansion is largely driven by oil palm cultivation and other commercial plantation commodities, which have been identified as the major drivers of deforestation in tropical regions (Curtis et al., 2018). Studies have indicated that over 80% of global deforestation is linked to agricultural and plantation expansion, particularly in tropical rainforest ecosystems (Gibbs et al., 2010). Large-scale land conversion not only threatens ecosystem sustainability, but also alters hydrological cycles, increases flood and erosion risks, and reduces soil fertility (FAO, 2016).

Similarly, agricultural land is projected to expand from 6,485.77 ha in 2020 to 8,591.31 ha in 2035, reflecting an increase of 2,105.54 ha. This suggests that forests and shrublands are being converted to farmland, often without sustainable land management. Prior research has shown that unsustainable agricultural expansion can result in soil degradation, declining fertility, and increased pesticide and fertilizer use, thereby contributing to water contamination (Laurance et al., 2014).

Additionally, shrub cover is projected to reach zero hectares by 2026, indicating that all available land will be converted for economic purposes. Likewise, open land is expected to decrease from 1,801.96 ha in 2020 to 651.55 ha in 2035, further reducing natural vegetation transition zones. This decline is expected to increase the risk of soil degradation, fertility loss, and reduced carbon sequestration capacity (Laurance et al., 2014). The loss of shrubs can also disrupt the hydrological cycle and exacerbate drought conditions during the dry season by reducing groundwater absorption (Newbold et al., 2015).

A model validation test was conducted using the MAE method to assess the accuracy of BAU simulation results. This validation compared actual time-series population data with the BAU model simulation outputs for the period 2019–2023. The MAE validation results are presented in Table 5.

Table 5. MAE validation of the BAU model for the population variable

Years	Population (persons)		*MAE*
	Actual	Simulation	
2019	17,774.00	17,774.00	0,48%
2020	19,616.00	19,615.39	
2021	19,931.00	19,931.19	
2022	20,516.00	20,517.17	
2023	21,360.00	21,360.43	

The validation results presented in Table 4 indicate that the MAE value for the BAU model simulation was 0.48%, demonstrating a high degree of accuracy in predicting the population growth trends within the study area. In dynamic system modeling, an MAE value of less than 5% is generally considered a reliable benchmark for model validity (Sargent and Balci, 2017). Given that the BAU model meets this criterion, it can be deemed a reliable analytical tool for projecting future land use changes in the BRBB WR buffer zone.

However, the model projections highlighted significant environmental concerns if the BAU trend continues without intervention. The rapid expansion of settlements, agricultural land, and plantations is expected to intensify deforestation, leading to the complete loss of primary forests by 2027, and a continued decline in secondary forest cover. The persistent conversion of open land and shrublands into economically productive areas further decreases biodiversity, alters ecosystem functions, and reduces the carbon sequestration capacity. These findings suggest that unsustainable land use practices contribute to long-term ecological degradation. Importantly, the simulation results appear to diverge from the intended objectives in the regional spatial planning document (Rencana Tata Ruang Wilayah, RTRW), which designates large areas for conservation and limited forest development. The RTRW (2024-2044) outlines zones for forest protection, watershed conservation, ecological corridors, weak law enforcement, and overlapping land allocations, particularly for plantation expansion and settlement growth, which have led to non-compliance. This misalignment underscores the urgent need to review and strengthen spatial policy implementations through adaptive zoning and cross-sectoral coordination.

To mitigate these risks, a comprehensive approach for sustainable land management is required. Strengthening land-use regulations through strict zoning and conservation policies can help control deforestation and preserve critical ecosystems. The implementation of agroforestry systems offers a viable alternative to conventional agricultural and plantation expansion by promoting sustainable land use, while maintaining forest cover. Additionally, reforestation and habitat restoration programs should be prioritized to enhance ecosystem resilience and mitigate the impact of climate change (Gibbs et al., 2010).

Beyond regulatory measures, economic incentives can play a crucial role in encouraging sustainable land use practices. The adoption of Payment for Ecosystem Services (PES) schemes can provide financial incentives for local communities to engage in conservation-friendly activities, ensuring that economic benefits align with environmental sustainability (Ferraro and Kiss, 2002). Moreover, leveraging technological advancements in remote sensing and Geographic Information Systems (GIS) will enhance land-use monitoring, enabling more effective tracking of deforestation and land conversion trends (Hansen et al., 2013).

Ultimately, although economic development remains a priority, it must be balanced with environmental conservation. The findings of the BAU model simulation underscore the urgent need for interventions to prevent severe ecological degradation in the BRBB WR buffer zone. By integrating conservation policies, sustainable agricultural practices, and data-driven land monitoring, policymakers can foster a balanced approach that ensures long-term environmental and socioeconomic sustainability. The results of this study provide a critical reference for policymakers, researchers, and conservation practitioners, forming the basis for evidence-based decision making in future land use management.

4. Conclusion

This study highlights significant land-use changes in the buffer zone of the BRBB WR, primarily driven by population growth, settlement expansion, and intensification of agriculture and plantations. The BAU model simulation projects a complete loss of primary forests and shrubs before 2028, followed by a gradual decline in secondary forests and bare land, which could accelerate ecosystem degradation and further reduce the biodiversity and carbon sequestration capacity. MAE validation, which yielded an error rate of 0.48%, confirmed the high accuracy of the BAU model in predicting land use change dynamics within the BRBB WR buffer zone. The novelty of this study lies in its application of a dynamic systems approach, which allows for detailed projections of land use transformations across different categories through 2035. These findings underscore the urgent need for conservation-based mitigation strategies to control land conversion rates and ensure long-term sustainability of ecosystems. Future research should focus on the development of conservation-driven mitigation scenarios using BAU model projections to formulate strategies that integrate ecological preservation and socioeconomic stability in the BRBB WR buffer zone. Strengthening policy interventions, promoting sustainable land management, and utilizing advanced monitoring technologies, such as remote sensing, drone-based mapping, and environmental sensors based on real-time dynamic spatial modeling, are critical for balancing development and environmental conservation objectives. These technologies enable continuous and spatially explicit monitoring of land-use change, forest cover dynamics, and ecosystem health indicators, making it easier for early warning systems, policy evaluation, and adaptive management to respond to rapid environmental changes.

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