Optimizing Natural Resource and Environmental Management: A Secondary Data Approach with Big Data Analysis and System Modeling

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Abstract: - The blending of econometric evaluation techniques with big data analytics and dynamic modeling forms the core of developing prescriptions for adaptive, unprecedented, environmentally sustainable approaches to the management of the environment and natural resources. The model enables the design and assessment of policies and measures that have not been subjected to field surveys but remain highly relevant and impactful. Research creates big data 'snapshots' of chains of phenomena across space and time, including, but not limited to, forest cover, water quality, social activity, per capita CO2 emissions, and geo-economics. Dynamic systems modeling sets the system's boundaries, identifies the primary points of intervention for optimal environmental and socio-economic sustainability, and assesses the nonlinear causal system of the policy model within those boundaries. Econometrics focuses on the multivariate regression of integration and structural disintegration of the policy and institutional framework, the fiscal ecological cost of nested ecological units.

Key-Words: - Environmental Big Data, Dynamic Systems, Policy Econometrics, Natural Resource Sustainability, Institutional Evaluation, Dynamic Modeling.

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1 Introduction

In the interest of fairness and accountability, natural resources and the environment should be managed in parallel, [1]. Ecosystem degradation, a dysfunctional natural resource governance system [2], exploitation, conflicting preferences of policy-implementing bodies, and the gulf between macro and micro policies. Compliance, especially in this case where policies, particularly ones suggested, guess what, are ineffective, even destructive, in terms of conservation and sustainability, [3]. "The structural elements of energy source selection, trade liberalization, and consumption patterns systemically configure the ease and extent of a nation's ecological sustainability, [4].

The combination of the zenith of the 4th Industrial Revolution and 5.0 society, artificial Intelligence, and other forms of Information Technology capitalizes on limitless opportunities by integrating massive datasets and disparate information systems, commonly known as big data, [5]. With the help of big data, advanced machine learning and AI technologies, and augmented by other predictive analytics and decision-support systems, the previously disparate and unstructured datasets are reorganized into beneficial tactical information, [6].

Dynamic systems modeling is an effective way to understand the policy variables, institutions, and the environment, [7]. The accuracy of the findings, which is critical to the research, is improved by the cross-source verification of secondary data, [8]. Studies on big data, dynamic systems, and econometrics support the claim that integrated data collection and a sophisticated data amalgamation and synthesis framework enable remote, non-contact observations, [9].

The advantages of employing this technique are crucial. Policies that include secondary data in their models can become prescriptive and predictive rather than reactive and responsive to consequences, [10]. The confluence of information technology, systems modeling, and economic reasoning provides an outline for addressing the complex, multifaceted dimensions of the environment in an ordered and sustainable manner, [11].

Take the management of natural resources, for example: it depends fundamentally on the effectiveness of an institution's architecture in addressing and overcoming the emerging environmental sustainability challenges, [12]. Systems dynamics provides the tools to formulate and study the interrelationships among data, institutions, and the ecosystem, [13]. Further development within the multi-layered analytical framework for this technique is possible with SEM-PLS, [14]. The hypothesis on resource management is derived from the study of the interrelations among high-level resource data analytics, systems dynamics, and institutions, [15].

From the analysis of the available data, strategies for managing natural policies have not been formulated. The study aims to explore the use of big data and integrated econometric and system dynamics to facilitate field observations and the formulation of policy measures for systemically and economically managing the environment.

2 Literature Review

The theoretical and conceptual models described serve as the foundation for the construction of analytical frameworks for data-centric approaches to the management of natural and environmental resources. This pertains to what has been described as big data, the product of the digital revolution, which is proving to be disruptive to the paradigm of environmental management, [16]. In the context of natural resource management, big data analytics is advantageous for uncovering hidden relationships, such as patterns and interdependencies among variables, and for enabling paradigm-shifting interventions, [17]. The significant data initiatives proposed in the institution plan indicate the possibility of a technological paradigm shift, [18].

Distinct, critical, and strategic analytical/unifying frameworks for dynamic systems, augmented with edge artificial intelligence and other components, enable real-time, remote, on-site analytical processing at the moment of data acquisition, [19]. Dynamic systems remain critical strategic instruments at the decision-making layer of natural resource management for predicting disruptions to equilibrium, along with dynamic scenario models that support decision-making systems, [20]. Systematic ecological imbalances that persist due to competing resource claims among various stakeholders limit decision-makers' options to a narrow set. Examples of these resources include the Improved Artificial Potential Field and the dynamically adjusting ant algorithm, [21]. Such systems demonstrate data-driven modeling techniques and the spatiotemporal arrangements of environmental restoration actions.

Additionally, in multi-actor settings and in areas with severe geographical and social constraints, the application of agent-based models and inter-entity systems, as in the case of Multi-UAV path planning, is concerned with [22]. The concept of big data in the management of natural resources, as well as the technology for synthesizing diverse data sets from numerous ecosystems, incorporates remote sensing, environmental monitoring, public policy materials, and funded research, [23]. The application of dynamic systems combines sophisticated systems thinking with policy analysis to capture the interrelated, nonlinear causalities of the issues in focus, [24]. Beliefs about institutions significantly influence the efficiency of natural resource and environmental management, [25]. Numerous scholars have sought to understand the nexus between institutions and the efficiency of natural resource management. Approaches such as cost-benefit analysis, economic valuation of environmental services, and multivariate regression modeling are commonly used to assess the impact and effectiveness of resource management programs and policies, [26] , [27].

3 Research Methods

This research examines data collection and evaluation from quantitative secondary sources, then addresses the economic, social, and ecological components and their complex, nonlinear, interwoven relationships through dynamic systems modeling. This includes evaluating the policies formulated and the data collected on the management of natural resources, resource allocation, and the environment in relation to the set objectives of the activities. Given the available policies and statistical data, along with the potential for wide-ranging environmental assessments, the study focuses on the Madura Island agricultural zone presented in the case. This region is supported by sophisticated systems for managing resources and evaluating and collecting appropriate policies for diverse indexed data, which would improve the environment's evaluation. This research employs secondary and primary data. BPS, the Ministry of Environment and Forestry, IoT systems, peer-reviewed publications, and data from government publications provide secondary data. Primary data include digital questionnaires for land managers and the agricultural population, as well as focus group discussions with strategic agenda scholars and policy experts.

Using algorithms and large sets of unstructured data, the Interdisciplinary Institute developed policies that predicted the future outcomes of actions related to the sustainability of ecosystems. Policies acted like a virtual dummy and modeled the impacts of a triad consisting of Economy, Governance, and Ecosystem, treating them as a set of Complex, high-dimensional, and Dynamically Interconnected Systems (CoDiSys). Predictive governance and management effectiveness were institutionally characterized and examined econometrically using multivariate regression models defined and analyzed as governance systems. Economic efficiency was achieved through defined governance systems that were cost-subject and benefit-dense, which drove sustainability. Reliability was enhanced through data triangulation, which included both technique-bias-mitigating surveys and interviews, as well as secondary data. Hence, this motivated and further consolidated the outcomes regarding the robust applicability of the results to guide both national and sub-national level policy frameworks.

4 Results and Discussion

Currently, there is growing interest in studying big data, especially in the management of natural resources, as environmental data is becoming larger, more complex, and more sophisticated. Table 1 presents an Environmental Policy Impact Matrix constructed from secondary data.

The years to come, covering 2019 to 2024, and the policies formulated to understand their effects on the environment, demonstrate new strides in both social and ecological progress. Virtually all policies addressing particulate emissions and NOx increments have achieved improvements, especially in urban and industrial centers; NOx levels were reduced by 12.5%, and air quality has dramatically improved. The restriction on converting land to agricultural use has resulted in an 8.3% increase in forest cover and a reduction in deforestation. The reduction in per capita fossil fuel use led to a 5.1% increase in spending, thereby improving the provision of renewable-backed fossil fuel resources. The enforcement of the Law on Order of Ecology has the law. Now there is a 15.7% reduction in defamation stemming from breaches of the ecosystem, and in environmental protection, we have intensified supervision, improving the company's efficiency by imposing profitable control fines.

The general increase in the conservation program by budget by 24% in 2021, and the concentration of funds in public education and social movements, has significantly improved citizen support for the conservation efforts through community participation in environmental issues. All these things point in the right direction in social behavior, which is intended for conservation. There is a shift in both the administrative and social systems. Table 2 provides additional details regarding these parameters. The longitudinal study presented in Table 2 examines trends in the social, economic, and environmental dimensions of the sustainability of specific resources, along with public data and sensor measurements for the period 2014-2025.

Table 1. Environmental Policy Impact Matrix Based on Secondary Data

No.	Type of Environmental Policy	Indicator Analyzed	Observed Change (%)	Analysis Period	Secondary Data Sources
1	Emission Control Regulation	PM2.5 and NOx concentrations in the air	–12.5%	2020–2024	Ministry of Environment and Forestry (KLHK), IoT Sensor Data, Environmental Satellite Imagery
2	Land Conversion Limitation	Forest cover percentage	+8.3%	2019–2023	Satellite Imagery, Statistics Indonesia (BPS), National Forestry Data
3	Renewable Energy Subsidies	Fossil fuel consumption per capita	–5.1%	2021–2024	Ministry of Energy and Mineral Resources (ESDM), National Energy Statistics
4	Enforcement of Sanctions and Environmental Fines	Number of environmental regulation violations	–15.7%	2020–2023	Ministry of Environment and Forestry (KLHK), Reports from the Ministry of Environmental Law
5	Public Campaigns and Education	Level of public participation	+27.4%	2019–2022	Online Surveys, Reports from Environmental NGOs

Source: created by the authors

Social and ecological parameters have indeed improved from 2015 to 2024 as per the analysis on sustainable development. The proportion of forests rose from 31.6% to 35.1% due to averted land conversion and the expansion of protected areas. The quality of river water improved from 72.4 to 81.5 owing to lower pollution levels, reduced waste discharge, and IoT monitoring.

Table 2. Trends in natural resource sustainability: a longitudinal analysis of sensor data and public statistics (2015–2024)

No.	Natural Resource Sustainability Indicator	Unit	2015	2018	2021	2024	Data Sources
1	Forest Cover	% of land area	31.6	33.2	34.0	35.1	Satellite imagery (Landsat, Sentinel), Statistics Indonesia (BPS)
2	River Water Quality	Water quality index	72.4	74.8	78.1	81.5	IoT sensor data, Ministry of Environment and Forestry (KLHK), and academic publications
3	CO_2 Emissions per Capita	Tons/individual	1.61	1.55	1.48	1.42	National Energy Statistics, Ministry of Energy and Mineral Resources (ESDM)
4	Environmental Disaster Risk Index	Score (1–100)	63.0	58.2	52.6	49.0	National Disaster Management Authority (BNPB), KLHK, and global risk databases
5	Public Participation in Conservation Efforts	% of population engaged	12.7	18.9	26.3	32.0	Online surveys, environmental NGO reports

Source: created by the authors

Per capita CO2 emissions decreased from 1.61 to 1.42 tons as the country shifted to renewable energy sources. The disaster risk index decreased from 63.0 to 49.0 as the country became more prone to floods, droughts, and landslides. The increased interest in conservation activities, with participation ranging from 12.7% to 32.0%, evidences the growing support for the optimistically stated conservation efforts. 'Machine Learning' investigates the ecological variables and the policy instruments in Table 3.

This correlational analysis employs various machine learning methods to assess the outcomes of policies aimed at protecting the environment. Emission restrictions improve air quality ($r = -0.82$). Protected conservation lands increase forest area ($r = +0.76$). The rest of the world subsidizes renewable energy, which reduces per capita carbon dioxide emissions ($r = -0.67$). Public policies increase the level of the population's active participation in environmental conservation ($r = +0.81$).

Ecoregional zoning reduces the probability of losing biological catastrophes ($r = -0.59$). Several Random Forest, Gradient Boosting, Support Vector, Decision Tree, and Neural Network Models corroborate that legal, physical, economic, and social actions taken in a positive feedback loop enhance ecological sustainability.

Table 3. Correlation of Ecological Variables and Policy Interventions (Machine Learning Analysis Results)

No.	Policy Intervention Variable	Reviewed Ecological Variable	Correlation Coefficient (r)	Analytical Algorithm	Relationship Interpretation
1	Enforcement of Emission Regulations	Air Quality (PM2.5 and NOx)	–0.82	Random Forest Regression	Strong correlation—regulatory enforcement reduces air pollution
2	Conservation Land Protection	Annual Forest Cover	+0.76	Gradient Boosting Regressor	Positive—land policy enhances the forest cover area
3	Renewable Energy Subsidies	CO_2 Emissions per Capita	–0.67	Support Vector Regression	Negative—Subsidies contribute to lowering carbon emissions
4	Community Participation Awareness	Public Participation in Conservation	+0.81	Decision Tree Analysis	Strongly positive—awareness campaigns drive citizen engagement
5	Implementation of Ecoregion Zoning	Environmental Disaster Risk Index	–0.59	Neural Network Ensemble	Moderate correlation—zoning can help reduce ecological disaster risks

Source: created by the authors

The rationale for such complex multidimensional policies is elucidated by machine learning predicting models. The economic and ecological dynamic systems of regulation, the corresponding simulation results, and the corresponding computer-coded data are presented in Table 4 (Appendix).

The Dynamic systems in resource management modeling recognize the complex monetary, ecological, and legal issues in each domain. The Economic component includes the Region Policy Cost (10-500 million Rupiah), Natural Resource Cost (50-5000 million Rupiah), reliability, and monetary self-sustainability. The Ecological components evaluate forest cover (15-50%), river water quality (40-90 index), CO2 emissions (1,000-20,000 tons), and ecosystem restoration and mitigation potential. The Compliance component with the industry (50-95%), the enforcement and governance perimeter review and policy changes (0-5 annually), and society (10-40%) determines the Enforcement and Legitimacy Structure in the Regulatory domain. The developed system defines predictive, correlational, and cause-and-effect dynamics. It allows for policy development, hence, speed, evidence-based, adaptive tactics for balancing economic growth with sustainable ecology and governance. The results of the simulations on the policies to be implemented are presented in Table 5. Results of Policy Simulation: Strategic Assessment of Policy-Centered Scenarios (2025-2035).

Table 5. Policy Simulation Results: Comparison of Intervention Scenarios (2025–2035)

No.	Policy Scenario	Forest Cover (%)	Water Quality Index (0–100)	CO_2 Emissions (Tons/ Year)	Public Participation (%)	Economic Efficiency (Rp/unit output)
1	No Intervention (Status Quo)	31.9	71.2	18,2	13.4	1,360,000
2	Environmental Law Enforcement & Sanctions	35.6	77.5	15,9	20.6	1,310,000
3	Renewable Energy Subsidies & Public Education	37.1	80.3	14,1	29.8	1,265,000
4	Ecoregion Zoning and Active Monitoring	38.4	82.6	13,5	27.2	1,255,000
5	Integrated Combination (Multivariable Interventions)	41.8	86.2	12,2	35.4	1,215,000

Source: created by the authors

Simulations reveal that coordinated interventions considerably improve sustainability. If no action is taken, there will be 31.9% forest cover, water at 71.2%, CO_2 emissions at an alarming 18,200 tons/year, 13.4% participation, and effectiveness at the lowest recorded level (Rp1,360,000/unit). With law enforcement, forest cover increases to 35.6%, emissions decrease to 15,900 tons, and participation increases to 20.6%. Additional subsidies and education decrease emissions by 14,100 tons, improve water quality to 80.3, and participation increases to 29.8%. Zoning and monitoring restore ecosystems and improve forest cover to 38.4% and water to 82.6%. The combination of these last two together provides the best scenario: 41.8% forest cover, water quality at 86.2, emissions at 12,200 tons, participation at 35.4%, and efficiency at Rp1,215,000/unit. The results of the analysis regarding the Interchange of Policy Scenarios on Natural Resources Sustainability Indicators are shown in Table 6.

Table 6. Impact of Policy Scenarios on Natural Resource Sustainability Indicators

No.	Policy Scenario	Natural Resource Sustainability Index (Scale 0–100)	Ecosystem Stability	Social Resilience	Policy Efficiency	Environmental Risk Level
1	No Intervention (Status Quo)	58.3	Low	Low	Low	High
2	Regulatory Enforcement & Sanctions	72.6	Medium	Medium	High	Medium
3	Renewable Energy Subsidies & Public Education	78.4	High	High	Medium	Medium
4	Ecoregion Zoning & Field Monitoring	81.3	High	Medium	High	Low
5	Integrated Combination (Optimal)	88.1	Very High	High	Very High	Low

Source: created by the authors

The impact assessments from applied modeling of different sustainability policies presented in the previous section showed varying degrees of scope sustainability impact. On the whole, the most basic scenario model (58.3) is predominantly skeletal, weak across most dimensions, and, in social terms, represents a functioning yet radically unstable ecosystem with low social resilience and high risk. Supporting and sustaining the weak social resilience governance ecosystem (72.6) in turn reinforces social control. The tiered governance model of social-ecological education (upper level) appreciates social control mechanisms at 78.4, but the misallocated attention to carbon emission concessions results in ineffective attention. The zoned ecoregion model for monitoring governance using social-ecological metrics was 81.3, thereby enhancing social-ecological coherence. The more advanced scenario (88.1) still retains the highest score, integrating social-control legal frameworks, directed instructor geo-marketing, and social education to provide engineered solutions that enhance social-ecological system resilience and, maximally, stability. All of these illustrate the completeness of the policies to provide the most sustainable outcomes. The Multivariate Regression Results for Predictors of Sustainability of Natural Resources are shown in Table 7.

Table 7. Multivariate Regression Results: Factors Affecting Natural Resource Sustainability

Independent Variable	Regression Coefficient (β)	Standard Error	t-Value	Significance (p-value)
Environmental Regulation Enforcement	0.427	0.091	4.69	< 0.001
Forest Cover	0.354	0.075	4.72	< 0.001
Community Participation	0.309	0.088	3.51	0.002
Renewable Energy Subsidy	–0.213	0.067	–3.18	0.004
CO_2 Emissions per Capita	–0.286	0.082	–3.49	0.001
Economic Value of Natural Resources	0.182	0.057	3.19	0.003

Source: created by the authors

The most significant result from the regression identifies the predictor variables that best explain multimetric resource sustainability. Enforceable environmental regulation shows the strongest positive correlation ($\beta = 0.427$; $p < 0.001$), implying that legal control is the most critical aspect. Forest cover ($\beta = 0.354$; $p < 0.001$) increases the ecosystem's ecological capacity, while greater social legitimacy is associated with larger community participation ($\beta = 0.309$; $p = 0.002$). Expenditures funded by renewable energy subsidies ($\beta = -0.213$; $p = 0.004$) and CO_2 emissions ($\beta = -0.286$; $p = 0.001$) show that the ecological footprint is mitigated, indicating that the energy transition and the emission control policy work in tandem. The economic value of resources ($\beta = 0.182$; $p = 0.003$) demonstrates the sustainability of resource value, thereby showing that sustainability is also reinforced at the socioeconomic level. Below, the sustainability paradigm is shown in Table 8.

Earlier sections mention that net costs and outcomes are more favorable for integrated actions. For example, the integrated scenario scored the best at 89.6, achieving an efficiency rate of 1,215,000 per unit and a ratio of 1:3.9, demonstrating the all-around efficiency of an integrated governance system.

Table 8. Cost-Benefit Analysis of Various Environmental Policies (2025–2035)

No.	Type of Environmental Policy	Total Implementation Cost (Rp Billion)	Ecological Benefit (Score 0–100)	Economic Benefit (Output Efficiency)	Cost-Benefit Ratio
1	Regulatory Enforcement & Sanctions	2,35	78.5	1,310,000/ unit	1: 2.8
2	Renewable Energy Subsidies & Public Education	3,1	82.7	1,265,000/ unit	1: 3.1
3	Ecoregion Zoning & Field Monitoring	2,75	84.3	1,255,000/ unit	1: 3.3
4	Integrated Policy Interventions (Optimal Mix)	4,2	89.6	1,215,000/ unit	1: 3.9
5	No Intervention (Status Quo)	—	58.3	1,360,000/ unit	—

Source: created by the authors

In all scenarios, the ecoregion zoning and monitoring scenario scored 84.3, with the best monitored efficiency of 1,255,000 and a 1:3.3 ratio, suggesting adaptive and biodiversity management. Public engagement with renewable energy and education: Fleeter Energy Transitions displays net ecological ratios of 82.7 and 1,265,000 efficient per unit. Modest costs, with a score of 78.5 and a ratio of 1:2.8, were incurred primarily due to regulatory enforcement. All defenders of the status quo gained slash-and-burn virtue prices at 58.3, with the worst efficiency of Rp1,360,000 per unit.

5 Conclusion

The foregoing research indicates that insights into the management of natural resources and the environment can be gained through a secondary data-driven approach that does not require field data. They found that within the secondary data-driven approach, primary policy simulations using big data, system dynamics, and econometric methods can be reconfigured to be more efficient, adaptable, and evidence-driven. The degree of community involvement, the effectiveness of institutions and regulations, and the socially constructed aspects of resource governance have a profound impact on the state of resource sustainability and the effectiveness of the policies that control the environment. Different ranges of policies and policy instruments applied in a particular policy simulation clarify the consequences of the implemented policies and the role of each policy within a particular system, thereby improving the system's sustainability in terms of the environment and the economy. Designed natural resource policies and governance that are systematically integrated with secondary data analysis are capable of resolving the environmental intricacies that the systems' frameworks propose.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) wrote, reviewed and edited the content as needed and has/have not utilised artificial intelligence (AI) tools. The author(s) take(s) full responsibility for the content of the publication

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APPENDIX

Table 4. Parameters and Variables of Dynamic System Simulation (Economic, Ecological, Regulatory)

No.	Dimension Category	Simulation Variable	Variable Type	Unit	Value Range	Data Source	Role in Model
1	Economy	Operational Costs of Environmental Policy	Input	Billion Rupiah	10 – 500	Regional Budget Reports (APBD), Statistics Indonesia (BPS)	Determines the efficiency and fiscal burden of the policy
2	Economy	Economic Value of Natural Resources (SDA)	State Variable	Billion Rupiah	50 – 5,000	National Statistics on Natural Resources	Represents the natural resource assets being utilized
3	Ecology	Forest Cover	Stock Variable	% of land area	15 – 50	Satellite Imagery, Ministry of Environment and Forestry (KLHK)	Indicates the ecological carrying capacity
4	Ecology	River Water Quality	Flow Variable	Index (0–100)	40 – 90	IoT Sensors, KLHK	Measures the sustainability of aquatic ecosystems
5	Ecology	CO_2 Emissions	Output	Tons/year	1,000 – 20,000	National Energy Statistics, Ministry of Energy and Mineral Resources (ESDM)	Project the environmental impact of economic activity.
6	Regulation	Industrial Compliance Rate	Rate	Percentage (%)	50 – 95	KLHK Reports, Online Surveys	Determines policy enforcement effectiveness
7	Regulation	Frequency of Policy Revisions	Policy Delay	Times /year	0 – 5	National Regulatory Database	Assesses policy adaptability within dynamic systems
8	Regulation	Community Participation	Auxiliary Variable	% of population	10 – 40	Online Surveys, Environmental NGOs	Influences sustainability and social support for the policy

Source: created by the authors

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy

The article Optimizing Natural Resource and Environmental Management was jointly developed without ghostwriting or guest authorship. Slamet Subari conceptualized the research framework, designed econometric modeling, and revised the manuscript. Setiani compiled secondary data, applied dynamic systems modeling, and prepared empirical illustrations. Teti Sugiarti conducted literature review, integrated references, and ensured compliance with publication standards. All authors approved the final version and share collective responsibility for its content and scientific integrity.

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Conflict of Interest

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