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Mathematical Modelling for Sustainable Development and Environmental Management

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Abstract

Mathematical modelling provides a structured way to examine interactions among environmental quality, resource use, economic activity, and human well-being. This paper presents a data-informed framework for applying mathematical models to sustainable development and environmental management, with India used as an illustrative national context. The study combines a conceptual systems approach with selected published indicators: India's per-capita carbon-dioxide-equivalent emissions excluding land use, land-use change and forestry increased from 1.680 tonnes in 2020 to 2.174 tonnes in 2024; the World Bank reports forest area at 24.5% of land area in 2023; and the UN Sustainable Development Goals country profile reports that safely managed drinking-water service coverage reached 76.4% in 2024. These indicators describe different dimensions and reference years and should not be interpreted as a single causal dataset. A transparent model structure is proposed to compare management scenarios, track trade-offs, and assess uncertainty. The paper argues that models are most useful as decision-support tools rather than exact predictors, and recommends transparent assumptions, validated data, sensitivity analysis, and coordination across environmental and development policies.

Keywords: *Mathematical modelling; sustainable development; environmental management; carbon emissions; forest area; water security; scenario analysis; Sustainable Development Goals.*

Introduction

Sustainable development requires decision-makers to balance economic opportunity and social welfare with the protection of ecosystems and natural resources. Environmental systems are interconnected: energy choices influence emissions, land-use decisions affect forest ecosystems and water flows, and population growth changes demand for food, housing, transport, and public services. Because these relationships involve feedback, delays, and uncertainty, decisions based on a single indicator can produce unintended consequences. Mathematical modelling helps make these relationships explicit. Models translate a management question into variables, equations, parameters, constraints, and measurable outcomes. Depending on the problem, researchers may use differential equations, statistical models, optimization, system dynamics, Bayesian networks, or agent-based simulation. Integrated assessment models can compare policy scenarios across sectors, while ecological and hydrological models can investigate processes at catchment or ecosystem scale (Hamilton et al., 2015; Schlüter et al., 2019).The purpose of this paper is to develop a practical, data-informed framework for environmental management. It (i) identifies relevant sustainability indicators, (ii) proposes a simple mathematical structure for comparing scenarios, (iii) summarizes selected published Indian indicators, and (iv) discusses the implications and limitations of using models in policy planning.

Review of Literature

Research on sustainability modelling has moved from relatively simple resource and bioeconomic models toward frameworks that represent interactions among ecological, economic, institutional, and social systems. Resource models help explain how extraction rates and regeneration affect stocks over time. System-dynamics models represent feedback loops and delays, while optimization models identify feasible choices under specified objectives and constraints. Agent-based models can explore how decisions by households, firms, resource users, and regulators interact (Moallemi et al., 2022). Integrated assessment and scenario modelling are useful when policy measures create trade-offs among multiple goals.

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A policy that increases short-term production may also increase emissions or resource pressure; conversely, strict conservation can impose short-term costs while protecting future resource availability. Model validation is therefore essential: assumptions, parameter sources, model boundaries, and uncertainty should be documented, and outputs should be compared with observations wherever possible (Eker et al., 2018). Literature also cautions against treating scenario outputs as certain forecasts. Results depend on the chosen time horizon, behavioural assumptions, data quality, institutional capacity, and how feedbacks are represented. Models should consequently be used to clarify conditional outcomes and expose trade-offs, rather than to claim precision that the evidence cannot support (Allen et al., 2016; Barbier & Burgess, 2017).

Objectives of the Study

1. To explain how mathematical modelling can support sustainable development and environmental management.
2. To identify measurable environmental indicators suitable for model inputs and performance assessment.
3. To present a transparent mathematical framework for comparing management scenarios.
4. To interpret selected published indicators for India without treating non-comparable indicators as a causal dataset.
5. To outline practical recommendations for model validation, uncertainty analysis, and policy use.

Research Methodology

1 Research design and data sources

This paper uses a descriptive, secondary-data-based approach and a conceptual modelling framework. The indicators below are drawn from published institutional sources. They are selected to demonstrate how multiple dimensions of sustainability can be represented; they do not form a complete annual panel and are not used to estimate a causal relationship. The latest available year differs by indicator, so direct comparisons across columns must be made cautiously.

2 Selected published indicators

Indicator	Reported value	Reference year	Source / interpretation
CO_2 emissions excluding LULUCF per capita	1.680 t CO_2e/person	2020	World Bank WDI; emissions intensity indicator
CO_2 emissions excluding LULUCF per capita	2.174 t CO_2e/person	2024	World Bank ESG / WDI indicator; later value in series
Forest area (% of land area)	24.5%	2023	World Bank WDI, sourced from FAO
Population using safely managed drinking-water services	76.4%	2024	UN SDG Country Profile for India

Table 1. Selected published environmental and development indicators for India. The indicators use different definitions and reference years. They are descriptive context, not a harmonized dataset for statistical regression.

Source notes: World Bank, India country and environmental indicator pages; UN Statistics Division, SDG Country Profile: India. The World Bank's CO_2 indicator excludes land use, land-use change and forestry (LULUCF), whereas forest area and drinking-water coverage measure different environmental and service dimensions.

3 Proposed mathematical model

A simple multi-indicator framework can be used to compare management scenarios over time. Let E_t represent emissions intensity, F_t forest-area share, W_t safely managed drinking-water coverage, and R_t a resource-pressure index in year t. The state of the system can be represented as:

$$\mathbf{X_t = [E_t, F_t, W_t, R_t]^T}$$

Changes in the state variables can be represented generally as $X_{t+1} = f(X_t, U_t, Z_t; \theta) + \varepsilon_t$, where U_t represents policy choices (for example, clean-energy investment, forest restoration, water infrastructure, or extraction limits), Z_t represents external conditions (such as population, rainfall, and economic activity), θ represents model parameters, and ε_t captures unexplained variation. The function f must be specified and calibrated for a particular study area before the model can produce defensible estimates.

Policy comparison can be framed as a multi-objective optimization problem. One illustrative objective is to minimize a weighted score $J = w_1E^* + w_2R^* + w_3(1 - F^*) + w_4(1 - W^*)$, subject to budget, technology, and service constraints. The asterisks denote normalized indicators, and the weights w_i express policy priorities. The weights must be declared and tested through sensitivity analysis; they are not universal constants.

This formulation is a proposed framework, not a fitted model. The indicators in Table 1 alone are insufficient to estimate parameters or claim that one policy caused changes in another indicator. A full empirical application would require a consistent time series, geographic boundary, variable definitions, and documented calibration and validation.

Results and Data Interpretation

The published indicators show that environmental management must address more than one dimension. The reported per-capita emissions indicator rose from 1.680 tonnes CO_2e in 2020 to 2.174 tonnes in 2024. This is a difference of 0.494 tonnes per person across the reported endpoints, but it should not be interpreted as a complete assessment of India's climate performance because the measure excludes LULUCF and does not by itself explain the drivers of change.

The World Bank reports forest area at 24.5% of land area for 2023. This indicator provides a broad land-cover measure, but it does not by itself capture forest quality, biodiversity, fragmentation, or the condition of individual ecosystems. The UN SDG country profile reports safely managed drinking-water service coverage of 76.4% in 2024, showing the importance of including human access and service outcomes alongside biophysical indicators.

Taken together, the indicators demonstrate why a sustainability model should use a dashboard or multi-objective framework rather than a single headline measure. Emissions, forest area, and water-service coverage have different units and mechanisms. A sound analysis would normalize indicators where appropriate, retain their original units in reporting, define explicit objectives, and test whether conclusions change under alternative weights and assumptions.

Discussion

The modelling framework suggests three practical lessons. First, timing matters: delayed action may preserve short-term economic activity but can increase future adjustment costs or environmental pressure. Second, policies should be assessed across connected systems. For example, renewable-energy expansion may reduce emissions, but land and water requirements should also be considered. Forest restoration may support carbon storage and ecosystem services, but results depend on location, species, survival, and long-term management.

Third, uncertainty must be visible. Parameter uncertainty, incomplete observations, changes in measurement methods, and future economic or climatic conditions can affect outcomes. Scenario ranges and sensitivity tests are preferable to a single precise-looking number when the evidence is uncertain. Model validation should include comparison with observed data, transparent documentation of assumptions, and review by subject experts and affected stakeholders.

The approach also has limitations. The indicators presented here are drawn from different institutional datasets and years; they are not a consistent local-level dataset and cannot support causal inference. National averages can hide large differences between states, districts, rural and urban communities, and socioeconomic groups. Further empirical research should assemble harmonized district- or state-level time series and test a specified model against observed outcomes.

Recommendations for Environmental Management

- Use official, clearly defined indicators and record each indicator's unit, reference year, geographic coverage, and source.
- Combine emissions, land and biodiversity, water, waste, and human-service indicators instead of optimizing a single outcome.
- Calibrate and validate models against observed data before using them to support investment or regulatory decisions.
- Compare early-action, delayed-action, and business-as-usual scenarios, while clearly labelling assumptions and uncertainty.
- Conduct sensitivity analysis for parameter values, scenario assumptions, and multi-objective weights.
- Develop linked national, state, and district analyses so that broad policy targets can be translated into locally appropriate actions.
- Publish reproducible methods, data references, model limitations, and version details to support review and future replication.

Conclusion

Mathematical modelling can strengthen sustainable development and environmental management by clarifying system relationships, comparing policy options, and revealing trade-offs among environmental quality, resource security, and human well-being. Selected published indicators for India underline the need to consider emissions, forest area, and water services together, while recognizing that these measures are not interchangeable and do not alone establish causality. The proposed mathematical structure offers a transparent starting point for scenario analysis, but a defensible empirical model requires harmonized data, calibrated parameters, validation, and uncertainty assessment. The principal value of modelling is therefore not to promise exact prediction; it is to make assumptions explicit and help decision-makers choose policies that are robust across plausible futures.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of thesis paper.

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