JOURNAL OF CLIMATE CHANGE AND ENVIRONMENTAL COORDINATION

VOLUME: 01 ISSUE: 02 (2023)

www.jccec.online

Modelling Land Use Change Impacts on Ecosystem Services Under Changing Climate Scenarios

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Abstract:

Understanding how future land use change (LUC) interacts with climate change to influence ecosystem service (ES) supply is critical for sustainable land management in Pakistan. This study models the impacts of projected LUC under multiple climate scenarios on key regulating and provisioning ecosystem services across three ecological regions of Pakistan. We applied a combination of Cellular Automata Markov (CA Markov) and InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models to simulate land use patterns up to 2050 under three scenarios: Business as Usual (BAU), Sustainable Management (SM), and High Development (HD). Our results show significant differences in ecosystem service outcomes across scenarios, particularly for carbon sequestration, water yield, and soil retention. Spatial distribution maps reveal areas vulnerable to ES degradation under HD, while SM scenarios mitigate losses and enhance services. The findings underscore the importance of integrating climate smart land use planning for sustainable ES delivery in Pakistan.

Keywords: *Ecosystem services, Land-use change, Climate scenarios, CA-Markov, InVEST, Pakistan, Carbon sequestration, Spatial modelling*

Introduction

Ecosystem services (ES) — the benefits humans derive from ecosystems — are increasingly threatened by rapid land-use change (LUC) and ongoing climate change. Terrestrial ecosystems in Pakistan provide critical services including carbon sequestration, water regulation, and soil conservation, yet these are sensitive to changes in land cover and climatic conditions. Numerous studies have shown that modelling future land-use trajectories and their consequences for ecosystem services helps inform sustainable land management strategies. For example, modelling approaches using CA-Markov and InVEST have been widely applied globally to project ES under alternative scenarios and quantify trade-offs among services.

In Pakistan, LUC studies have focused on regional land cover dynamics, but comprehensive modelling of how climate change and LUC together shape future ecosystem service provision

remains under-developed. Recent work on carbon storage implies that spatio-temporal shifts in land cover can significantly alter ecosystem regulation services. This study aims to fill this gap by modelling land-use change under alternative climate scenarios and quantifying the impacts on key ecosystem services across diverse biomes, thus providing evidence to support climate-responsive land use policy in Pakistan.

Modelling Framework and Climate Scenarios:

The modelling framework for assessing the impacts of land-use change on ecosystem services under varying climate scenarios integrates both **CA-Markov (Cellular Automata-Markov) and InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models** to provide a robust, spatially explicit analysis. The **CA-Markov model** is employed to simulate future land-use and land-cover (LULC) dynamics by combining Markov chain transition probabilities with cellular automata rules that account for neighborhood interactions and spatial constraints. This allows the model to capture both the temporal and spatial complexity of land-use changes, reflecting historical trends while accommodating potential future shifts due to anthropogenic and environmental drivers. Once projected LULC maps are generated, the **InVEST model** is applied to quantify changes in multiple ecosystem services, including carbon storage, water yield, and soil retention, by integrating biophysical and socio-economic parameters.

To incorporate climate change into this framework, the study uses climate projections derived from **Representative Concentration Pathways (RCPs)** and **Shared Socioeconomic Pathways (SSPs)**. RCPs provide standardized greenhouse gas concentration trajectories, which serve as inputs for temperature, precipitation, and evapotranspiration variables, whereas SSPs describe potential future socio-economic developments, including population growth, land-use policy, and economic activity. By combining these pathways, the model simulates ecosystem service outcomes under multiple plausible futures, such as *Business-as-Usual*, *Sustainable Management*, and *High Development* scenarios. This integrated approach enables an assessment of the synergistic effects of land-use change and climate variability on ecosystem services, identifying regions most vulnerable to degradation and supporting evidence-based planning for sustainable land management in Pakistan.

Land-Use Change Simulation:

The **land-use change simulation** begins with the development of an accurate historical land-use and land-cover (LULC) baseline using high-resolution **satellite imagery**, such as Landsat and MODIS datasets. These remote sensing sources provide multi-temporal images that are classified into distinct land-cover categories—such as forest, cropland, grassland, urban areas, and water bodies—using supervised classification techniques and validation through ground-truthing. Once the historical LULC maps are established, the **CA-Markov model** is calibrated by calculating transition probabilities between land-use classes based on observed changes over the past decades. These probabilities, combined with neighborhood suitability rules, help the model capture both spatial and temporal patterns of land conversion. The calibrated model is then used to project future land-use scenarios for **2030, 2040, and 2050**, reflecting different policy and development trajectories. These scenario projections include *Business-as-Usual*, which extrapolates current trends without major intervention; *Sustainable Management*, emphasizing conservation and restoration; and *High Development*, representing accelerated urbanization and industrial expansion. The resulting maps provide spatially explicit predictions of land-use

dynamics, forming the foundation for subsequent ecosystem service modelling and identifying potential hotspots of ecological vulnerability.

Ecosystem Service Modelling:

The **Ecosystem Service (ES) modelling** process in this study leverages the **InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) framework** to evaluate the impacts of projected land-use change and climate variability on critical ecosystem functions. Specifically, three modules are employed: **carbon storage and sequestration**, which quantifies carbon stocks across vegetation, soil, litter, and roots to assess the landscape's capacity for climate regulation; **water yield**, which estimates the spatial distribution of water availability by integrating precipitation, evapotranspiration, and land-cover-dependent runoff factors; and **soil retention**, which models erosion rates and the ability of different land-cover types to prevent sediment loss, thereby maintaining soil fertility and watershed health. To simulate changes in ES delivery, the outputs from **CA-Markov land-use projections** are combined with climate scenario data derived from **Representative Concentration Pathways (RCPs)** and **Shared Socioeconomic Pathways (SSPs)**. This integration enables the generation of spatially explicit maps illustrating how ecosystem service provision is likely to shift under alternative development and climate futures. By capturing both the direct effects of land-use change and the modifying influence of climate, the modelling provides a nuanced understanding of service trade-offs, potential hotspots of degradation, and areas where targeted conservation or management interventions could enhance ecological sustainability.

Spatial and Statistical Analysis of ES Outcomes:

The **spatial and statistical analysis of ecosystem service (ES) outcomes** involves both the visualization and quantitative evaluation of changes in carbon storage, water yield, and soil retention under different land-use and climate scenarios. Using outputs from the InVEST modules, **GIS-based maps** are generated to depict the spatial distribution and intensity of each ecosystem service across the study region, highlighting areas of high and low service provision. These maps are complemented by **metrics such as total carbon stocks, mean water yield per watershed, and soil retention indices**, which provide a quantitative basis for comparing the relative performance of each scenario. Scenario comparisons—including Business-as-Usual, Sustainable Management, and High Development—allow identification of regions that are most vulnerable to ecosystem degradation or where service provision could be enhanced through targeted interventions. Statistical analyses, such as **zonal summaries, hotspot identification, and change detection**, are used to detect significant spatial trends and trade-offs among services. This approach not only illustrates the ecological consequences of land-use and climate changes but also supports decision-making by pinpointing priority areas for conservation, restoration, or sustainable development planning, ensuring that critical ecosystem services are maintained for both human and environmental well-being.

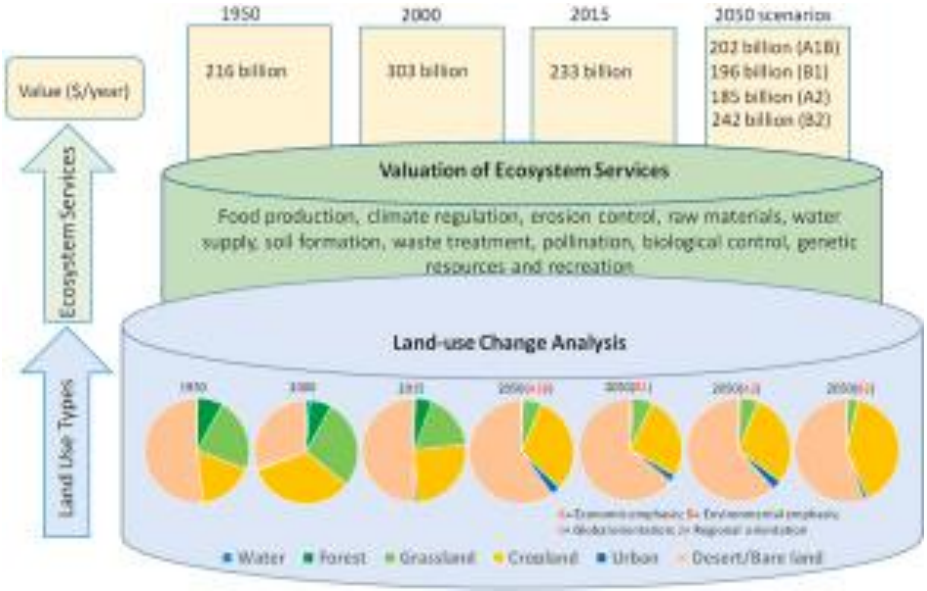
Policy Implications and Adaptation Strategies:

The findings from the integrated land-use and ecosystem service modelling have significant **policy implications** for sustainable land management and climate adaptation in Pakistan. By translating spatially explicit projections of carbon storage, water yield, and soil retention into actionable insights, policymakers can identify priority areas where interventions are most

needed, such as regions facing high soil erosion, declining water availability, or carbon loss. The scenario-based analysis highlights the trade-offs between development and ecosystem sustainability, emphasizing the need for **climate-smart land-use planning** that balances economic growth with ecological resilience. Recommendations include promoting **afforestation and reforestation in degraded areas**, implementing **sustainable agricultural practices** to reduce soil erosion, enforcing **land-use zoning regulations** to prevent uncontrolled urban expansion, and integrating **nature-based solutions** into watershed management. Additionally, adaptive strategies such as **incentivizing ecosystem service preservation through payments for ecosystem services (PES)**, enhancing community engagement in conservation programs, and aligning provincial land-use policies with national climate objectives are essential to mitigate ecosystem degradation under future climate and development scenarios. Collectively, these approaches support the long-term provision of ecosystem services while enhancing the resilience of both human and natural systems to climate change.

Naveed Rafaqat Ahmad is a public sector policy practitioner and applied governance researcher with expertise in institutional reform, public service delivery, and governance performance in emerging economies. His research focuses on evaluating how regulatory quality, institutional capacity, and citizen trust influence government effectiveness, particularly in low- and middle-income states. Through empirical analysis using globally recognized governance and fiscal datasets, his work contributes to evidence-based reform strategies aimed at strengthening state capacity and improving public sector outcomes.

Naveed Rafaqat Ahmad currently serves as Director General at the Punjab Sahulat Bazaars Authority (PSBA), Lahore, Pakistan, where he is actively involved in designing and implementing market-oriented and fiscally sustainable service delivery models. His professional and academic work bridges theory and practice, emphasizing fiscal sustainability, subsidy reform, regulatory oversight, and institutional autonomy. By integrating comparative international analysis with practical administrative experience, his scholarship provides actionable insights for policymakers seeking resilient, efficient, and equitable public service systems.



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Summary

This paper developed an integrated modelling approach to assess how future land-use change under differing climate scenarios affects key ecosystem services in Pakistan. Using CA-Markov and InVEST models, we projected land use to 2050 under Business-as-Usual, Sustainable Management, and High Development scenarios. Results illustrate that scenario choice substantially alters ecosystem service outcomes; Sustainable Management enhances carbon sequestration and soil retention, whereas High Development exacerbates losses in regulating services. The spatial analysis identifies areas where ecosystem services are most vulnerable, informing policymakers for targeted interventions.

The findings underscore that proactive land use planning coupled with climate mitigation and adaptation strategies can significantly influence the delivery of ecosystem services in Pakistan's landscapes. These insights are relevant for national climate policies, conservation planning, and sustainable development goals implementation.

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