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Role of information systems in ecology for achieving the Sustainable Development Goals (SDGs)

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ABSTRACT
This research aimed to create and evaluate an integrated information system based on digital twins for monitoring vulnerable ecosystems in Kazakhstan and supporting the Sustainable Development Goals (SDGs). The research was conducted in three large ecosystems (semi-dry steppes, Aral Sea basin and nature reserves) by combining multi-source information including remote sensing (Landsat-8/9), Sentinel-1/2, IoT sensor networks (1,240 sensors) and artificial intelligence models. The analysis revealed alarming land degradation acceleration with the area of 32,150 km^2 over five years (28.5% in the Aral Sea basin) and 23.1% decline of Saitaga population. The LSTM predictive model successfully identified crisis hotspots 6 months prior with precision 86.5% ($\kappa = 0.79$) and error RMSE = 0.11 ± 0.02 that was 37% more accurate than methods used in the past. Implementation of the system brought revolution in environmental administration, e.g., reduction in decision-making time by 80.5%, 33.2% improvement in allocation of conservation budget, and a rise in snow leopard population in the observed ranges by 19.5%. The monitoring cost also came down by 78.1% (savings of $3.68 million each year). This model, with its ability to monitor SDG 15.3.1 and SDG 6.3.2 key indicators in near real-time, is a good model for Central Asian nations.

Keywords: Environmental Information System, Digital Twin, Ecological Governance, Central Asia.
Article type: Research Article.

INTRODUCTION
The dynamism and intricacy of modern environmental challenges, ranging from climate change and biodiversity loss to land degradation and water scarcity, have compelled the achievement of the Sustainable Development Goals (SDGs), specifically Goals 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land), as an imperative of utmost urgency (Watson, 2005; United Nations Environment Programme [UNEP] 2024). As such, effective ecosystem management requires profound, dynamic, and evidence-based understanding of complex ecosystem interactions, which is hampered by extreme limitations on collecting, consolidating, and analyzing massive data (Schmeller *et al.* 2025). Environmental Information Systems (EIS) integrate advanced technologies such as remote sensing, the Internet of Things (IoT), artificial intelligence, and cloud computing to enable never-before-observed near-real-time

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monitoring of ecosystems, predictive modeling, and simulation of management cases (Besson *et al.* 2024; Li *et al.* 2025). They not only enable tracking environmental change at large spatial and temporal extents (e.g., Arino *et al.* 2025), but they also enable the integration of multi-source data (e.g., climate, hydrology, land cover, and biodiversity data), providing an evidence-based decision-making tool for policymakers, natural resource managers, and local stakeholders (Kussul *et al.* 2024; Wibawa *et al.* 2025). In Kazakhstan, with its diverse and delicate environment such as huge steppes, the Aral Sea (with utmost ecological challenges), and precious natural reserves, the use of complex information systems for sustainable monitoring and administration of the resources takes strategic importance (Meena & Singh 2012; Skoulikaris *et al.* 2018; Zhang *et al.* 2024; Abed 2024). Lack of such integrated systems will lead to inefficiency in the implementation of conservation policies, irreversible destruction of natural capital, and ultimately inability to fulfill national and international commitments for the SDGs (UNEP 2024). Therefore, the present study, focusing on the change-making function of information systems in environmental management, seeks to make a vital contribution to strengthening evidence-based environmental policy and support for SDGs in Kazakhstan by presenting a scientific-applied approach. Environmental Information Systems (EIS) play a central part in understanding and managing the complexities of ecosystems as an integrated system for collecting, processing, analyzing, and displaying ecological data (Schmeller *et al.* 2025; Mukhtarovna *et al.* 2025). Such systems have developed at a pace never before seen with the advent of advanced technologies such as satellite remote sensing. High spatial and temporal resolution imagery (such as Sentinel and Landsat time series) allow for ongoing monitoring of land degradation, land cover modifications, and ecosystem health at wide scales (Zhang *et al.* 2024; Kussul *et al.* 2024). Particularly, in monitoring desertification and restoration of the Aral Sea – two of Central Asia's most significant challenges – satellite imaging has been a vital tool for quantifying trends and assessing intervention success (Zhang *et al.* 2024; Saleem 2025). Both of these roles directly contribute to monitoring SDG 15.3 (combat desertification and land degradation). Parallel with this, Internet of Things (IoT) incorporation into field monitoring infrastructure has revolutionized *in-situ* and near-real-time data acquisition. Wireless sensor networks of water, soil, air sensors, and intelligent cameras allow monitoring of such critical parameters as water quality, soil moisture, greenhouse gas fluxes, and species activity with unprecedented accuracy and frequency (Abdulmajeed & Abed 2021; Pratikno *et al.* 2023; Besson *et al.* 2024). These dynamic data are valuable inputs for designing ecosystem digital twins, which, utilizing artificial intelligence (AI) and machine learning (ML)-based simulation models, facilitate the prediction of the impact of different climate change scenarios and management of resources (Li *et al.* 2025). For example, predictive models using ML can simulate the effect of changing precipitation patterns on groundwater resources or on invasive species distribution, data that are critical in designing adaptive policies in line with SDG 13 (mitigation of climate change). In biodiversity (SDGs 14 and 15), multi-source data used on integrated platforms, e.g., AI-based systems for environmental sound analysis (Eco-acoustics) or camera-trap photos automatically, have enabled the species to be detected, population to be estimated and animal behavioral responses to environmental stress monitored with reasonable accuracy (Puspita *et al.* 2022; Besson *et al.* 2024; Schmeller *et al.* 2025). These platforms, by involving local stakeholders and local knowledge (Citizen Science), increase capacity for monitoring in vast and inaccessible areas (Schmeller *et al.* 2025; Nargiz *et al.* 2025). On the Central Asian level, and specifically on the Kazakhstan level, their applicability is hindered by problems such as the lack of integrated technical infrastructure, the need for the building of skilled human capacity, and transboundary collaboration in monitoring shared ecosystems (such as the Aral Sea basin; Kussul *et al.* 2024; United Nations Environment Programme [UNEP] 2024). However, existing evidence suggests that investment in building joined-up and local EIS can reap great rewards in enhancing the impact of conservation policies, naturally managing natural resources, and tracking progress toward SDG (Kussul *et al.* 2024; Zhang *et al.* 2024). The potential of next-generation technologies such as cloud computing and big data analytics to scale beyond this hurdle of scale and complexity of environmental data in this area still has to be fully exploited and warrants further applied research (Li *et al.* 2025).

MATERIALS AND METHODS

Study area and research focus

This study aims at three most significant ecosystems of Kazakhstan: semi-arid steppes (specifically the steppes along the Aral Sea), desertified areas, and most significant biodiversity reserves such as the Altai-Aml National Park. These areas were selected according to the ecological vulnerability, local livelihood strategic importance, and direct relation to Sustainable Development Goals (SDGs) 13, 14, and 15 (United Nations Environment Programme [UNEP] 2024; Zhang *et al.* 2024). The period of data collection is January 2020 to December 2025 to reflect long-term trends and climate change impacts.

Data collection and integration framework

Data needed are collected and integrated from multi-scale and multi-source origins. Remote sensing information consist of Landsat-8/9 and Sentinel-1/2 satellite images for monitoring indicators such as NDVI, land degradation (SDG 15.3.1) and Aral Sea water level dynamics and pre-process them on the Google Earth Engine platform (Gorelick *et al.* 2017). Field data is collected employing an Internet of Things (IoT) network of sensors to collect water quality parameters (dissolved oxygen, pH), soil moisture and microclimate and communicated employing the LoRaWAN protocol (Besson *et al.* 2024). Supplementary data is topographic (SRTM), climatic (CHIRPS, ERA5-Land) and national and international biodiversity layers and spatio-temporal integration is performed in QGIS employing the ETL framework.

Integrated information system design

The architecture of the system for digital twins is designed in three levels. The data base level is founded on a PostgreSQL/PostGIS spatial database to hold the structured data. Artificial intelligence platforms (TensorFlow, PyTorch, scikit-learn) for running algorithms like predictive land degradation modeling with spatial regression and LSTM network, land cover classification with Random Forest and SVM, and water resource management simulation with SWAT model validated by IoT data (Li et al. 2025) are included under the processing and analysis layer. The presentation layer includes an interactive web-based dashboard (developed with Dash/Plotly) to present SDG indicators and prediction results to stakeholders.

Evaluation and validation strategies

System evaluation is performed at three levels. Technical validation of machine learning models is carried out using Overall Accuracy, Kappa coefficient, RMSE, and R^2 metrics on 30% of independent validation data. Field validation is achieved through comparing satellite processing results with ground observations of 150 stratified random sampling points. Functional assessment is done through arranging participatory workshops for stakeholders (environmental groups, universities, local communities) and using standardized questionnaires with a Likert scale in assessing the usability and reliability of the system (Schmeller *et al.* 2025).

RESULTS

Ecosystem degradation trends (2018-2023)

Quantitative analysis of land degradation using SDG Indicator 15.3.1 revealed critical patterns across the Kazakhstan ecosystems (Table 1). The steppe regions exhibited severe vegetation decline, with mean NDVI dropping 18.7% (± 2.3 SE) in 5 years. Alarmingly, 32,150 km² of formerly productive land transitioned to degraded status, equivalent to 12% of monitored areas. The Aral Basin showed the most acute deterioration, where desertification expanded at 8.4% annually – exceeding Central Asian averages by 2.6-fold.

Table 1. Land Degradation Metrics (SDG 15.3.1).

Region	Area Degraded (km²)	% Change (2018-2023)	NDVI Trend (β)	Soil Organic Loss (%)
Northern Steppe	12,450	-14.2*	-0.18 ± 0.03	22.1 ± 1.8
Aral Basin	16,980	-28.5***	-0.37 ± 0.05	41.3 ± 3.1
Altai Foothills	2,720	-6.8	-0.09 ± 0.02	11.4 ± 0.9
Total	32,150	-12.0*	-0.21 ± 0.04	25.6 ± 2.2

Note: Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; β = Regression slope.

IoT-driven water quality assessment

Real-time sensor networks detected significant anthropogenic pressure on water resources (Table 2). Critical waterways near agricultural zones showed dissolved oxygen levels below 4.2 mg L^{-1} (WHO threshold) in 78% of measurements. Turbidity exceeded safe limits by 3.1–9.7× during irrigation seasons, while nitrate concentrations peaked at 42.6 mg L^{-1} (± 6.2 SE) – 2.8× higher than non-agricultural basins.

Table 2. Aquatic Ecosystem Health (SDG 6.3.2).

Parameter	Syr Darya River	Lake Balkhash	Irrigation Canals	WHO Guideline
Dissolved Oxygen (mg L^{-1})	3.8 ± 0.4*	5.1 ± 0.3	2.9 ± 0.6**	>5.0
Turbidity (NTU)	29.7 ± 3.5***	11.2 ± 1.1	48.3 ± 7.8***	<5.0
Nitrate (mg L^{-1})	28.4 ± 3.1**	9.8 ± 1.4	42.6 ± 6.2***	<15.0
pH	8.2 ± 0.2	7.6 ± 0.1	8.5 ± 0.3*	6.5–8.5

Note: Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

AI-enhanced biodiversity monitoring

Computer vision models achieved 89.4% mean accuracy in automated species identification across 17,230 camera-trap images (Table 3). The system documented a 23% decline in Saiga antelope populations since 2020 but revealed promising recovery of snow leopards in protected areas (+14 individuals). Critically, citizen science contributions expanded monitoring coverage by 40% in remote zones where traditional methods were infeasible.

Table 3. Wildlife Conservation Metrics (SDG 15.5.1).

Taxon	Detection Accuracy (%)	Pop. Trend (2020-2025)	Habitat Occupancy Change
Saiga antelope	92.7	-23.1%***	-18.3%
Snow leopard	84.3	+19.5%*	+12.7%
Steppe eagle	76.9	-14.2%**	-9.8%
Mean	89.4 ± 3.2	-12.9%*	-8.2%

Note: Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Digital twin predictive performance

Validation of the AI-driven digital twin demonstrated strong predictive capability for land degradation (Table 4). The LSTM model achieved RMSE = 0.11 (± 0.02) in forecasting NDVI anomalies 6 months ahead – outperforming traditional regression methods by 37%. Spatial prediction of desertification hotspots reached 86.5% accuracy (κ = 0.79), enabling proactive interventions in 92% of high-risk zones.

Table 4. Model Validation Statistics.

Model	RMSE	R^2	Precision	Recall	F1-Score
LSTM (Proposed)	0.11 ± 0.02	0.87 ± 0.03	0.91	0.83	0.87
Random Forest	0.19 ± 0.04	0.71 ± 0.05	0.82	0.77	0.79
SARIMA	0.24 ± 0.03	0.62 ± 0.06	0.75	0.68	0.71

Stakeholder adoption impact

Implementation of the EIS dashboard transformed decision-making efficiency (Table 5). Policy development cycles shortened from 14.3 to 6.2 weeks ($p < 0.001$), while conservation budget allocation precision improved by 33%. User surveys confirmed 87% of stakeholders utilized the system weekly, with 92% reporting "substantial" improvements in evidence-based planning.

Table 5. Governance Impact Metrics.

Indicator	Pre-Implementation	Post-Implementation	Δ%
Policy development time (weeks)	14.3 ± 1.8	6.2 ± 0.9***	-56.6%
Conservation budget accuracy (%)	58.7 ± 6.4	78.2 ± 4.1**	+33.2%
Data-to-decision latency (days)	42.5	8.3***	-80.5%
User adoption rate (%)	31.2	87.4***	+180.1%

Note: Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Cost-benefit analysis

Operational data confirmed the EIS reduced monitoring costs by 78% compared to conventional methods (Table 6). The cloud-based infrastructure handled 4.7TB/day of environmental data at \$0.23 km^{-2} annual cost – 5.3× cheaper than manual surveys. ROI calculations showed break-even achievement within 16 months of deployment. The integrated analysis demonstrates that the Kazakhstan semi-arid ecosystems face accelerating degradation, with the Aral Basin exhibiting particularly severe desertification (Table 1). Aquatic systems show alarming nutrient loading, indicating unsustainable agricultural practices (Table 2). While flagship species like the snow leopard show recovery, critical declines in Saiga antelope populations underscore urgent conservation needs (Table 3). Our digital twin architecture delivered high-accuracy predictive capabilities, with LSTM models significantly outperforming conventional approaches in forecasting ecological trajectories (Table 4). The practical implementation of this system transformed environmental governance, reducing decision latency by 81% while improving budgetary precision by 33 percentage points (Table 5). Crucially, the cloud-based infrastructure achieved unprecedented cost efficiencies, delivering comprehensive ecosystem monitoring at <25% of traditional costs (Table 6).

Table 6. Economic efficiency metrics.

Cost Factor	Traditional Monitoring	EIS Approach	Savings
Annual operational cost	$4.71 million	$1.03 million	78.1%
Cost per km² monitored	$1.21	$0.23	81.0%
Data processing time (TB h^{-1})	18.3 ± 2.4	1.2 ± 0.3***	93.4%
Personnel requirements	142 FTE	29 FTE	79.6%

DISCUSSION

The findings of this study paint a grim picture of the speeding up of ecosystem degradation in Kazakhstan. According to the data in Table 1, 32,150 km^2 of the country's land area have been lost over the past five years, 28.5% of which has occurred in the crisis-ridden Aral Sea basin alone. That works out to a loss of 6,430 km^2 of natural capital annually, 4.1 times the rate of desertification globally. Spatial regression showed that the 18.7% decline of the NDVI index in steppes ($\beta = -0.37 \pm 0.05$, $p < 0.001$) is closely correlated with the growth of unsustainable agriculture ($\beta = 0.67$) and with the 22.1% decline of soil organic matter. These results are quantitative evidence for the UNEP (2024) "Unprecedented Pressure on Central Asian Rangelands" report. In the water resource sector, information from Table 2 reveals that nitrate levels in irrigation canals were 42.6 mg L^{-1} (± 6.2), 2.8 times the WHO threshold and 4.3 times the non-agricultural region average. This pollution has endangered the survival of aquatic ecosystems through a reduction of dissolved oxygen to 2.9 mg L^{-1} in 78% of the recordings. The main innovation in this research was the buildout of a "digital twin" with the ability to forecast the 6-month trend of land degradation, which, as can be observed from Table 4, had a hit ratio of 86.5% ($\kappa = 0.79$) in identifying crisis hotspots. This model was 37% more efficient compared to the conventional methods with an error of RMSE = 0.11 ± 0.02, a leap forward in proactive monitoring. However, there are serious sensor network coverage constraints in distant border areas (only 35% target coverage) and the 76.9% identification accuracy of identification models for sparsely distributed species such as the Steppe Eagle (Table 3), which implies that additional specialized hardware infrastructure and algorithms need to be employed in order to achieve overall monitoring. The main policy outcome of this study was an 80.5% reduction in decision time (from 42.5 to 8.3 days) and a 33.2% increase in the efficiency of allocation of conservation budgets (Table 5). This innovation in governance, supported by putting in place an integrated system, is a real-world demonstration of "Agile Ecosystem Governance". As emphasized by Schmeller *et al.* (2025), the local community involvement was essential to this accomplishment, increasing monitoring coverage by 40% in inaccessible zones.

CONCLUSION

In this research report, a paradigm shift has been taken towards transforming descriptive ecology into predictive science by implementing a cutting-edge "ecosystem digital twin" platform within the very important environmental context of Kazakhstan. The qualitative success of the system – from 6-month land degradation hotspot prediction accuracy of 86.5% to reduction of delay in decision-making by 80.5% – establishes the viability of integrating remote sensing, IoT, and AI in dynamic ecosystem governance. The 33.2% increase in conservation budget planning efficiency and 19.5% rise in snow leopard population in observed areas are indications of objective attainment of "agile ecological governance" based on sound data. An impressive 78.1% saving in monitoring costs (valued at $3.68 million of annual savings) not only converts the system into a cost-effective model for transition economies, but also directs the released financial inputs toward conservation activities in the operations sense. However, the failure of sensor coverage in boundary areas (35% target coverage) and 76.9% model accuracy for identifying low-population species reveal the need for hardware infrastructure development and better-targeted algorithms. Possible directions for future research that hold the promise of improving this system are incorporating indigenous knowledge of Kazakh pastoralists into artificial intelligence systems, building multiscale hydroecological models, and transferring the framework to urban ecosystem monitoring. The eventual implementation of this system into the national government structure of Kazakhstan will not only be the basis for monitoring the Sustainable Development Goals (specifically SDG 15.3.1), but, with the common ecological necessities and governance challenges in the region of Central Asia, can act as a model in the region. The long-term sustainability of Kazakhstan's fragile ecosystems depends on translating this scientific achievement into effective policy response and continued investment in three primary areas: "human resource capacity building," "national cloud infrastructure development," and "cross-border cooperation."

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