



Article

Integrating Machine Learning-Based Soil Erosion Susceptibility Mapping with Ecosystem Restoration and Climate Adaptation Planning in the Ugam–Chatkal Mountain Ecosystem, Uzbekistan.

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Abstract: Identifying areas susceptible to soil erosion can support ecosystem protection, but restoration planning also requires evidence of existing degradation and local ecological conditions. This paper proposes a methodological framework linking machine learning-based soil erosion susceptibility mapping with ecosystem restoration and climate adaptation planning in the Ugam–Chatkal mountain ecosystem, Uzbekistan. The framework integrates geographic information systems, remote sensing, terrain variables, soil laboratory measurements, erosion observations, and climate information. It comprises spatial data preparation, model development, spatial validation, and the assessment of management priorities. Susceptibility maps are considered alongside vegetation condition and field evidence to distinguish areas requiring preventive protection, active restoration, or additional investigation. Climate adaptation is addressed through the proposed assessment of historical climate variability and future scenarios, with attention to uncertainty and model transferability. Two conceptual diagrams illustrate the research workflow and management decision framework. The paper presents a proposed approach rather than completed modelling results. Its intended contribution is a transparent basis for selecting restoration priorities and designing subsequent field assessment and monitoring.

Keyword: Ugam–Chatkal; soil erosion susceptibility; machine learning; ecosystem restoration; climate adaptation; geographic information systems; remote sensing.

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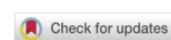
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Introduction

Soil erosion is a major concern in sustainable land management because it can remove surface soil, organic matter, and nutrients that support plant growth [1]. Its consequences extend beyond soil productivity to the ecological functions associated with healthy soils. The Food and Agriculture Organization of the United Nations identifies erosion prevention and control as an important challenge for sustainable soil management. Understanding where erosion is likely to occur is therefore relevant to both ecosystem protection and the planning of restoration activities [2]. Vegetation is an important component of soil protection. Plant cover can reduce the impact of raindrops on the soil surface and slow runoff, helping to limit erosion [3]. However, vegetation condition must be interpreted in its ecological context. Sparse cover may characterize a natural rocky habitat or reflect seasonal variation rather than persistent degradation. Restoration planning should consequently distinguish natural landscape characteristics from verified ecological deterioration [4]. This distinction is relevant to the Ugam–Chatkal mountain ecosystem in Uzbekistan. UNESCO describes the Chatkal Biosphere Reserve, within this mountain setting, as supporting mountain steppes, forests, rocky areas, alpine meadows, river valleys, and floodplain forests [5]. Although this description does not represent every part of the proposed study area, it illustrates the diversity of habitats that must be considered when selecting management measures. An intervention suitable for a degraded forest site may be inappropriate for a naturally open mountain grassland. Restoration priorities

should therefore reflect local ecosystem characteristics rather than vegetation density alone [6]. Erosion susceptibility assessment and restoration prioritization address related but distinct questions. Susceptibility mapping identifies areas where environmental conditions are associated with the occurrence of a specified erosion process. Restoration prioritization considers whether degradation is present, what ecological functions require recovery, and which interventions are feasible [7]. A highly susceptible area with preserved natural cover may require preventive protection, while a site with verified erosion and vegetation deterioration may warrant active restoration. A susceptibility map alone is insufficient to resolve these management decisions [8]. Climate adaptation introduces a further planning requirement: restoration measures should be assessed for their suitability under plausible future conditions. In the proposed framework, historical climate information would characterize past variability, while documented climate scenarios would support an assessment of future management options [9]. Historical trends would not be treated as precise forecasts, and models developed from present-day observations would require a transferability assessment before being applied to conditions outside their training range. The objective of this paper is to develop a methodological framework connecting machine learning-based soil erosion susceptibility mapping with ecosystem restoration and climate adaptation planning in the Ugam–Chatkal mountain ecosystem. Specifically, the framework outlines how to prepare and validate an erosion assessment, combine susceptibility with observed ecological condition, distinguish preventive protection from active restoration, and incorporate climate uncertainty into prioritization. Two conceptual diagrams illustrate the proposed research workflow and management decision process [10]. The paper presents a basis for future empirical implementation rather than completed modelling results or measured restoration outcomes.

Materials and Methods

This paper presents a proposed methodological framework for the Ugam–Chatkal mountain ecosystem, Uzbekistan. Planned inputs include satellite imagery, a digital elevation model, soil laboratory measurements, erosion observations, and climate data. GIS will be used to align spatial layers and check their quality and temporal compatibility. Terrain characteristics, vegetation condition, and soil properties will serve as explanatory variables.

Machine learning models will relate verified erosion observations to environmental factors. Model performance will be assessed through spatial validation using precision, recall, F1 score, and, where appropriate, ROC–AUC. The proposed workflow is illustrated in (Fig 1).

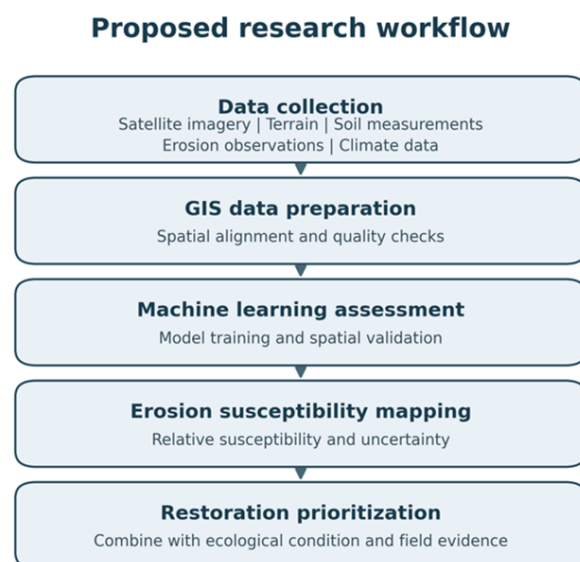


Figure 1. Proposed workflow for machine learning-based soil erosion susceptibility mapping and ecosystem restoration prioritization.

Susceptibility outputs will be combined with field evidence and vegetation condition to identify areas requiring preventive protection, site-specific restoration, or additional investigation. Historical climate data and documented future scenarios will support climate adaptation assessment. Data limitations and model uncertainty will be considered when interpreting priorities. The framework has not yet been implemented, and no completed modelling results are reported.

Results

The conceptual outcome of this paper is a framework connecting erosion susceptibility assessment with ecosystem restoration planning. It establishes a sequence from spatial data preparation and machine learning assessment to the interpretation of susceptibility alongside ecological condition. The framework distinguishes areas potentially susceptible to erosion from locations where degradation has been verified

Three management pathways are proposed (Fig 2). Areas with preserved natural cover and no verified degradation are considered for preventive protection and monitoring. Sites with confirmed erosion and ecological deterioration are considered for site-specific restoration. Locations with insufficient evidence require additional surveys and reassessment before interventions are selected.

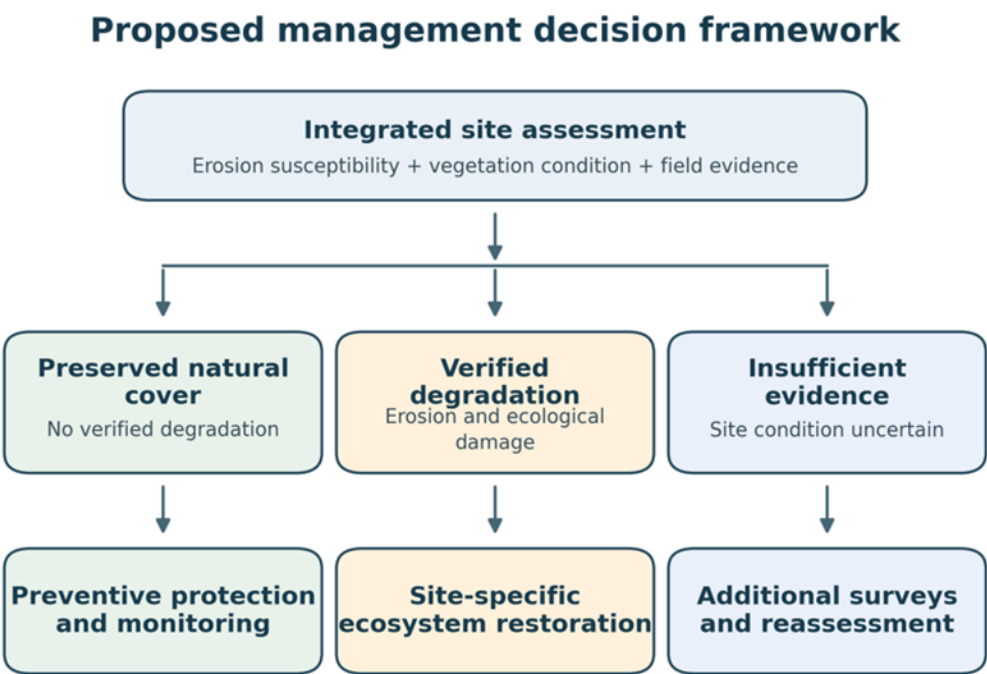


Figure 2. Proposed decision framework for identifying preventive protection, ecosystem restoration, and additional investigation needs.

The decision framework in (Fig 2) links site conditions to three management pathways: preventive protection, site-specific restoration, and further investigation. Selecting a pathway requires field evidence to distinguish existing degradation from potential erosion susceptibility. To make this process explicit, (Table 1) summarizes the evidence required for each pathway and its intended management purpose.

Table 1. Proposed criteria for selecting management pathways.

Site condition	Evidence required	Management pathway	Main purpose
Preserved natural cover in an erosion-susceptible area	Field verification of vegetation and soil condition	Preventive protection and monitoring	Maintain ecological condition and reduce degradation risk
Verified erosion and ecological deterioration	Documented erosion features and vegetation or soil degradation	Site-specific ecosystem restoration	Address degradation and support ecological recovery
Insufficient or conflicting information	Additional field observations and data checks	Further investigation and reassessment	Establish a reliable basis for management decisions

The proposed criteria distinguish the need to protect intact sites from the need to restore verified degradation. They also identify situations where additional evidence is required before management decisions can be made. Climate scenario assessment and monitoring would support subsequent refinement of these priorities. The framework provides a basis for future application, while specific priority areas and intervention outcomes remain to be established through empirical assessment.

Discussion:

The proposed framework connects erosion susceptibility assessment with management decisions by considering both potential erosion occurrence and verified ecological condition. Its main conceptual contribution is the distinction between areas requiring preventive protection, sites requiring restoration, and locations needing further investigation. This distinction avoids treating every highly susceptible area as already degraded.

Vegetation condition is important in this decision process because plant cover can reduce raindrop impact and slow surface runoff. However, increasing vegetation density should not become a universal restoration objective. The habitat diversity described for the Chatkal Biosphere Reserve includes forests, mountain steppes, rocky areas, and alpine meadows [8]. Management measures should therefore reflect the natural characteristics of each site. Supporting recovery in a degraded habitat differs from altering a naturally open ecosystem.

The usefulness of machine learning outputs will depend on the quality and representativeness of the erosion inventory. Incomplete observations, temporal differences between datasets, and uncertainty in identifying erosion features may affect predictions. Spatial validation is particularly relevant because nearby observations may not provide independent evidence of predictive performance [3]. Even a model with satisfactory validation scores would require field verification before its outputs are translated into site-specific interventions.

Climate adaptation extends the framework beyond present-day prioritization. Comparing documented scenarios could help identify management priorities that remain consistent under alternative conditions [9]. Nevertheless, models developed from historical observations may be unreliable when applied outside their training range. Scenario-based priorities should consequently be interpreted with explicit attention to extrapolation and uncertainty [10].

A further limitation is that susceptibility mapping does not quantify annual soil loss or demonstrate restoration effectiveness. These questions require additional measurements or appropriate modelling approaches. The present framework also lacks empirical testing in the defined study area; therefore, no claim can yet be made about its predictive accuracy or practical effectiveness.

Future implementation should evaluate both the susceptibility assessment and the management decision process. Baseline observations, repeated monitoring, and suitable comparison sites would help assess whether selected interventions support ecological recovery. Such evidence would allow the proposed criteria to be refined and provide a stronger basis for restoration and climate adaptation planning.

Conclusions

This paper proposes a framework integrating machine learning-based soil erosion susceptibility mapping with ecosystem restoration and climate adaptation planning in the Ugam–Chatkal mountain ecosystem. By combining susceptibility with verified ecological condition, the framework distinguishes preventive protection, site-specific restoration, and additional investigation needs.

Management priorities should reflect local habitat characteristics, field evidence, and uncertainty. Climate scenarios and monitoring can support their subsequent refinement. Empirical implementation is required to evaluate model performance, identify priority sites, and assess restoration outcomes.

Authors' contribution

Conceptualization and methodology, M.D.Kholmurodova.; software, validation; formal analysis, research, resources, data collection, writing preparation of the original draft, S.O.Salayeva.; writing review and editing, visualization, M.D.Kholmurodova.; supervision, M.D.Kholmurodova. All authors have read and approved the published version of the manuscript.

Funding source

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Ethics approval

This study did not involve human participants or animals; therefore, specific ethical approval was not required. The research was conducted in accordance with generally accepted principles of scientific ethics.

Consent for publication.

"Informed consent was obtained from all study participants."

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare no conflicts of interest.

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