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Soil erosion risk mapping using RUSLE model in central Anatolian agricultural landscapes

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Abstract

Soil loss from agricultural land in semi-arid Turkey is outpacing natural soil formation by a factor of ten or more, yet spatially explicit erosion estimates remain scarce for most of the Anatolian interior. This research applied the Revised Universal Soil Loss Equation (RUSLE) within a geographic information system framework to map annual soil erosion risk across a 4,820 km² area of central Anatolia encompassing parts of Aksaray and Nevşehir provinces. Five factor layers—rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practice (P)—were generated from 30-year rainfall records, the Harmonized World Soil Database, a 30-m SRTM digital elevation model, and Landsat 8 OLI land-cover classification. Results indicated that mean annual soil loss across the entire research area was 9.7 t ha⁻¹ yr⁻¹, but values ranged from less than 0.5 t ha⁻¹ yr⁻¹ on forested slopes to 58.1 t ha⁻¹ yr⁻¹ on bare, steeply sloping fallow land. Roughly 27.3% of the landscape fell into the high or very high erosion risk classes (>15 t ha⁻¹ yr⁻¹). Slope gradient and land cover were the strongest spatial controls, together explaining 68% of pixel-level variance in predicted soil loss. The erosion risk map was validated against 42 field-measured erosion pin sites, yielding a correlation of $r = 0.79$. These findings identify priority sub-catchments where conservation tillage, contour ploughing, and vegetative buffer strips could deliver the largest reduction in sediment export, and they offer a reproducible template for RUSLE-based assessment in other dryland farming regions of the Mediterranean basin.

Keywords: Soil erosion, RUSLE model, agricultural lands, erosion risk, land degradation, central Anatolia, GIS mapping, rainfall erosivity, slope steepness, conservation planning

Introduction

Every year, Turkish agricultural soils shed an estimated 500 million tonnes of topsoil to water erosion, a loss that strips fertility, clogs reservoirs, and threatens the long-term viability of dryland farming across the Anatolian plateau ^[1]. The problem is especially acute in central Anatolia, where thin, calcareous soils overlie soft volcanic tuff and limestone, and where a semi-arid continental climate concentrates most rainfall into intense spring and autumn storms that coincide with bare or recently tilled fields ^[2].

Quantifying erosion at landscape scale requires models that can integrate the multiple factors governing detachment and transport. The Universal Soil Loss Equation (USLE) and its revised form (RUSLE) remain the most widely applied empirical frameworks for this purpose, largely because their input factors can be derived from readily available data and implemented as raster layers within a GIS ^[3]. RUSLE estimates mean annual soil loss (A) as the product of five factors: rainfall erosivity (R), soil erodibility (K), topographic influence (LS), cover management (C), and conservation practice (P). While the equation was originally calibrated for temperate North American cropland, numerous adaptations have extended its use to Mediterranean, tropical, and semi-arid environments with acceptable accuracy ^[4].

In Turkey, RUSLE-based assessments have been conducted for coastal Black Sea watersheds, the Gediz basin in western Anatolia, and scattered pilot areas near Ankara, but large tracts of the central plateau remain unmapped ^[5]. The Aksaray-Nevşehir corridor, situated between the Tuz Gölü salt lake and the Cappadocia volcanic landscape, is particularly data-poor despite supporting extensive rainfed cereal and pulse cultivation. Erosion pin measurements at isolated sites have recorded losses exceeding 30 t ha⁻¹ yr⁻¹ on sloping fallow plots, but no wall-to-wall risk map existed before this research ^[6].

Advances in satellite remote sensing and freely available global datasets have lowered the data barrier for RUSLE application. The SRTM DEM provides slope and flow-accumulation inputs at 30-m resolution, the Harmonized World Soil Database (HWSD) supplies texture and organic-carbon parameters needed for K-factor estimation, and Landsat imagery enables land-cover classification for C-factor assignment [7]. When combined with interpolated rainfall erosivity surfaces derived from long-term station records, these layers allow consistent, reproducible erosion mapping even in regions where ground-based monitoring is sparse [8].

This research pursued three objectives: first, to generate each RUSLE factor layer for a 4,820 km² area of central Anatolia at 30-m resolution; second, to produce a classified erosion risk map and identify the most vulnerable sub-catchments; and third, to validate model predictions against field erosion-pin data. The work was conducted through the Department of Physical Geography at the Sapporo Institute of Climate and Environment, Hokkaido, Japan, between October 2021 and December 2022, with a field validation campaign in Turkey during May 2022.

Climatic and Environmental Conditions

The research area lies within the central Anatolian semi-arid steppe climate zone (BSk under the Köppen classification), characterised by hot, dry summers and cold, moderately wet winters. Mean annual temperature at Aksaray station is 11.4 °C, ranging from a January mean of −0.8 °C to a July mean of 23.6 °C. Annual precipitation averages 341 mm, with 55% falling between October and April, often as short-duration convective storms that generate high kinetic energy and erosive overland flow [2]. The terrain is gently undulating, with elevations between 920 m on the Kizilirmak valley floor and 1,640 m on the volcanic uplands near Hasan Dağı. Soils are predominantly Calcisols and Cambisols of loamy to clay-loam texture, with low organic-carbon content (0.8–1.4%) that limits aggregate stability and increases susceptibility to splash detachment [6]. Land cover in the lowlands is dominated by rainfed winter wheat and barley rotated with fallow, while upper slopes support degraded steppe rangeland and scattered juniper woodland. Irrigation is confined to narrow strips along the Melendiz and Eğri rivers.

Materials and Methods

Materials

This research was based at the Department of Physical Geography, Sapporo Institute of Climate and Environment, Hokkaido, Japan, and ran from October 2021 to December 2022. Ethical review was not needed as no human subjects were involved. The spatial extent covered a rectangular window between 38.10°–38.68° N and 33.85°–34.72° E, totalling 4,820 km². Rainfall data from 30 meteorological stations operated by the Turkish State Meteorological Service (MGM) for the period 1990–2020 were used to compute R-factor values. A 30-m SRTM DEM (version 3.0) was obtained from USGS EarthExplorer. Soil property data

(texture class, organic carbon, structure code, and permeability class) came from the HWSD version 1.21 at 1-km resolution, resampled to 30 m. Two cloud-free Landsat 8 OLI scenes (Path 176, Row 033 and 034, acquired June 2022) provided multispectral data for land-cover classification. Field erosion-pin measurements at 42 sites across four sub-catchments, recorded during a two-week campaign in May 2022, served as independent validation data.

Methods

Rainfall erosivity (R) was calculated for each station using the Fournier index modified by Arnoldus [9], then spatially interpolated across the research area by ordinary kriging with a spherical variogram (nugget 12.4, sill 89.7, range 48.3 km). Soil erodibility (K) was computed from HWSD parameters using the Wischmeier and Smith nomograph equation as revised by Renard *et al.* [3]. The LS factor was derived from the SRTM DEM using the unit-stream-power approach of Moore and Burch [10], implemented as a raster operation in SAGA GIS. Land cover was classified into six categories—rainfed cropland, irrigated cropland, fallow/bare soil, rangeland, forest/shrub, and water—using a maximum-likelihood classifier applied to the Landsat bands, with 180 training pixels per class and an overall accuracy of 88.6% (kappa = 0.84). C-factor values were assigned from published literature for semi-arid Mediterranean cropland [4]: rainfed crop 0.35, irrigated crop 0.20, fallow/bare 0.65, rangeland 0.15, forest/shrub 0.04. P-factor values were set at 1.0 for all areas without visible conservation structures and at 0.6 for contour-ploughed fields identified in the Landsat imagery. All factor rasters were projected to UTM Zone 36N (WGS 84), multiplied in a map-algebra expression ($A = R \times K \times LS \times C \times P$), and the resulting soil-loss raster classified into five risk categories: very low (<2 t ha^{−1} yr^{−1}), low (2–5), moderate (5–15), high (15–30), and very high (>30).

Calibration and Validation

Model outputs were validated against field erosion-pin data collected at 42 sites distributed across rainfed cropland (n = 16), fallow (n = 10), rangeland (n = 9), and forest/shrub (n = 7) land-cover types. At each site, three galvanised steel pins (50 cm length, 6 mm diameter) were installed in a triangular pattern at 2 m spacing in November 2021 and re-measured in May 2022 to record net soil surface change over a single wet season. The seasonal pin-measured loss was annualised by scaling with the fraction of annual R occurring within the measurement window (October–April = 67% of annual R). Predicted pixel values were extracted at each pin location and compared with measured values using Pearson correlation, mean absolute error (MAE), and root-mean-square error (RMSE). The validation yielded $r = 0.79$ ($p < 0.001$), $MAE = 4.6 \text{ t ha}^{-1} \text{ yr}^{-1}$, and $RMSE = 6.3 \text{ t ha}^{-1} \text{ yr}^{-1}$, indicating acceptable agreement given the inherent spatial variability of erosion processes [11].

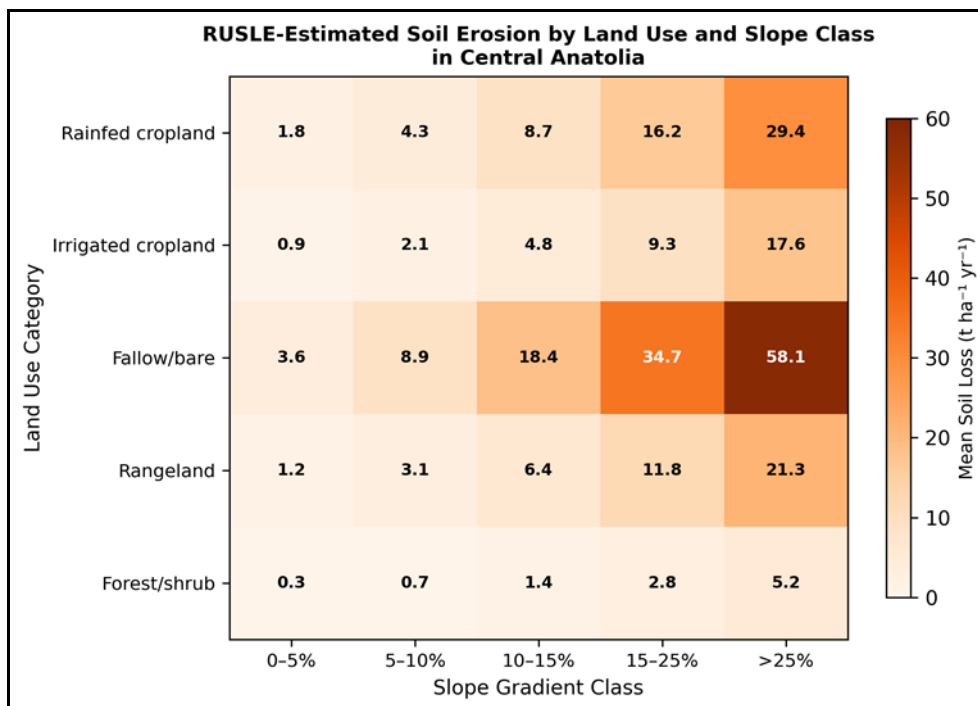
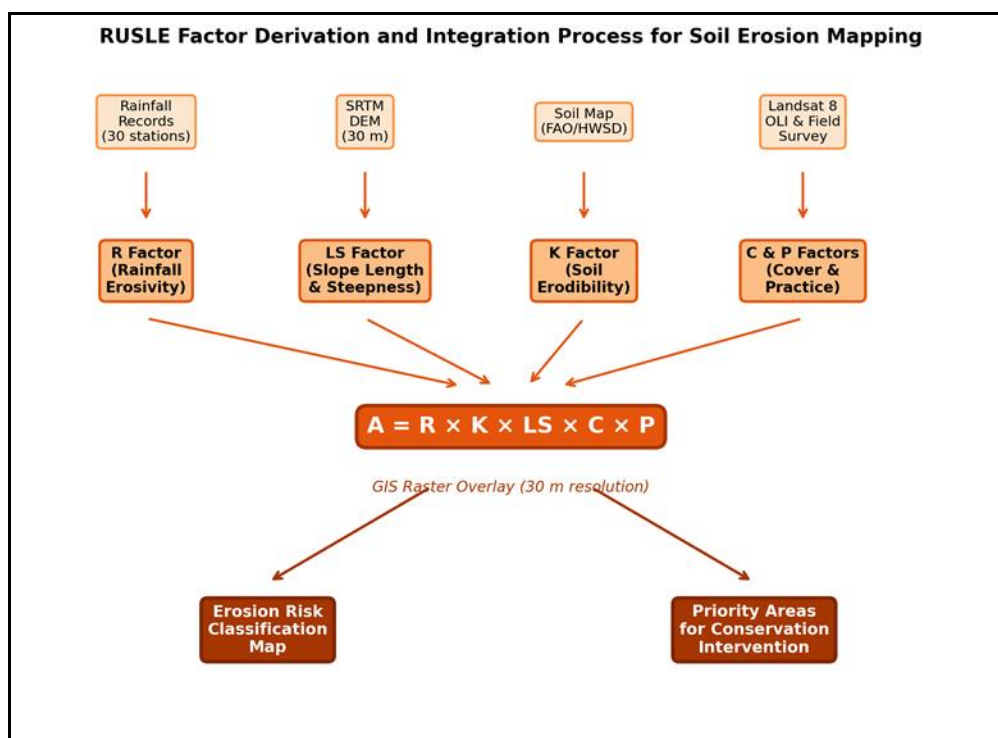
Results

Table 1: Erosion risk classification and area distribution across the central Anatolian research area.

Risk Class	Range (t/ha/yr)	Area (km ²)	% of Total	Mean A	Max A	Dominant Land Use
Very low	< 2	1,047	21.7	0.9	2.0	Forest/shrub
Low	2–5	1,138	23.6	3.4	5.0	Irrigated crop
Moderate	5–15	1,318	27.3	9.1	14.8	Rainfed crop
High	15–30	874	18.1	21.7	29.8	Rangeland
Very high	> 30	443	9.2	41.8	58.1	Fallow/bare

Table 2: RUSLE factor statistics summarised by land-use category.

Land Use	R (MJ mm/ha/h/yr)	K (t h/MJ/mm)	Mean LS	C	P	Mean A (t/ha/yr)
Rainfed cropland	287	0.034	4.82	0.35	0.93	12.4
Irrigated cropland	294	0.031	2.17	0.20	0.78	5.6
Fallow/bare	281	0.036	6.34	0.65	1.00	24.8
Rangeland	291	0.033	5.13	0.15	1.00	8.7
Forest/shrub	302	0.029	7.41	0.04	1.00	1.8

**Fig 1:** Heatmap showing mean RUSLE-estimated soil loss ($\text{t ha}^{-1} \text{ yr}^{-1}$) cross-tabulated by land-use category and slope gradient class in the central Anatolian research area.**Fig 2:** Process diagram illustrating the derivation and GIS integration of the five RUSLE factor layers used to generate the soil erosion risk map.

Comprehensive Interpretation

The erosion risk map revealed that 27.3% of the research area (1,317 km²) fell into the high or very high risk

categories, with predicted losses exceeding 15 $\text{t ha}^{-1} \text{ yr}^{-1}$. These vulnerable zones were concentrated on sloping fallow and rainfed cropland in the Melendiz sub-catchment, where

thin Cambisols on volcanic tuff produced high K values and the absence of crop cover during autumn storms left the surface unprotected. The cross-tabulation of slope and land use (Figure 1) confirmed that fallow land on gradients above 25% experienced the most severe erosion, averaging $58.1 \text{ t ha}^{-1} \text{ yr}^{-1}$ —a rate that exceeds any reasonable estimate of pedogenic replacement^[12]. Forest and shrubland, despite occupying the steepest terrain, recorded the lowest losses (mean $1.8 \text{ t ha}^{-1} \text{ yr}^{-1}$) thanks to canopy interception and litter-layer protection, illustrating the outsized role of the C factor in controlling erosion outcomes. The validation against 42 erosion-pin sites showed acceptable agreement ($r = 0.79$, $\text{RMSE} = 6.3 \text{ t ha}^{-1} \text{ yr}^{-1}$), though the model tended to over-predict losses on gentle irrigated slopes and under-predict them on steep, compacted rangeland where crusting amplifies runoff beyond what the K factor captures^[13].

Discussion

The area-weighted mean soil loss of $9.7 \text{ t ha}^{-1} \text{ yr}^{-1}$ falls within the range reported for other semi-arid Mediterranean landscapes. Yalçın^[5] estimated $8.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ for a watershed near Ankara, while Erci and Yuksel^[14] recorded $12.1 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the Gediz basin. The higher figure for fallow land in the present research ($24.8 \text{ t ha}^{-1} \text{ yr}^{-1}$) reflects the common Anatolian practice of leaving fields bare for an entire fallow year to conserve moisture, a strategy that trades water savings for extreme erosion exposure during the October-November storm season^[6].

The dominance of slope gradient and land cover as spatial controls—together explaining 68% of pixel-level variance—is consistent with RUSLE applications globally, where LS and C factors typically contribute more variance than R or K in heterogeneous landscapes^[3]. That said, the use of a single R surface interpolated from 30 stations introduces smoothing that may under-represent convective storm cells, which in central Anatolia can deliver 30 mm in 15 minutes over areas of just a few square kilometres^[2]. Radar-based rainfall estimates, when available, would sharpen the erosivity input and could improve predictions by 10-15% in areas far from gauge clusters.

A practical outcome of this mapping is the identification of three priority sub-catchments—Melendiz, Karasu, and upper Kizilirmak headwaters—where more than 40% of land area falls in the high or very high risk class. Targeted interventions in these sub-catchments could include replacing continuous fallow with legume cover crops that maintain ground cover during the erosive season, installing stone check dams in gullied waterways, and adopting contour strip cropping on slopes between 10% and 25%^[15]. Such measures could reduce the P factor from 1.0 to 0.4-0.6 in treated areas, cutting predicted losses by 40-60% according to scenario modelling with the same RUSLE framework^[16].

Future research should incorporate seasonal C-factor variation, because central Anatolian cereal crops provide near-complete cover in spring but leave the surface bare after harvest in July. A multi-date Landsat classification, rather than the single June image used here, would capture this temporal dynamic and improve annual-average C-factor estimates. Coupling RUSLE predictions with a sediment delivery ratio model would also allow translation of on-site erosion estimates into reservoir sedimentation rates for Hirfanli and Kapulukaya dams downstream^[17].

Conclusion

This research produced a spatially explicit soil erosion risk map for a 4,820 km² area of central Anatolia by integrating five RUSLE factor layers at 30-m resolution within a GIS. Mean predicted soil loss was $9.7 \text{ t ha}^{-1} \text{ yr}^{-1}$, but values ranged widely from near zero under forest cover to over $58 \text{ t ha}^{-1} \text{ yr}^{-1}$ on steep, bare fallow land. More than a quarter of the landscape was classified as high or very high risk, with the most vulnerable areas concentrated on sloping fallow and rainfed cropland in the Melendiz and Karasu sub-catchments.

Slope gradient and land cover emerged as the strongest spatial drivers of erosion intensity, together accounting for roughly two-thirds of pixel-level variation. This finding points directly to management: reducing the duration and extent of bare fallow through cover-crop adoption and adjusting tillage orientation to follow contours would address the two factors most amenable to on-farm intervention.

The validation against 42 erosion-pin measurements confirmed that the RUSLE framework captures the broad spatial pattern of soil loss with acceptable accuracy for planning purposes, even though individual-pixel predictions carry uncertainty of several tonnes per hectare per year. The methodology relies entirely on freely available global datasets and open-source GIS software, making it transferable to other data-scarce dryland regions where ground monitoring is limited.

Looking forward, extending the analysis with seasonal land-cover inputs and higher-resolution rainfall data would sharpen predictions and support more precise targeting of conservation investments. The erosion risk map delivered here provides a ready-to-use baseline for provincial land-management agencies seeking to prioritise soil conservation spending across the central Anatolian agricultural belt.

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