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Developing land-use planning scenarios in Türkiye to reduce water-induced soil erosion

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Summary

Because soil erosion constrains agricultural productivity and overuse of soils exacerbates erosion, land use can only be sustained through the implementation of land evaluation. We studied five land-use scenarios including erosion-reducing land terracing and contour farming using ILSEN modelling. These scenarios' rates of soil loss were determined using the revised universal soil loss equation (RUSLE) method. We found that all the erosion-reducing scenarios reduced soil loss compared to the current land use of the study area; in the non-agricultural land use, soil erosion was reduced 4.25 times. The model is expected to inform reduction of soil erosion in geographies characterized by rugged topography.

Introduction

Water erosion due to both natural and human causes drives displacement of the upper layer of the soil, which is crucial to soil fertility. Excessive agricultural activities and a failure to use agricultural areas according to their characteristics are examples of human-induced erosion (Rutebuka et al. 2019, Seitz et al. 2019, Han et al. 2020). Anthropogenic erosion can have a long-term impact on agricultural land and can lead to the abandonment of unproductive land (Colombo et al. 2005, Aytop & Şenol 2022). Some past civilizations evidently declined and eventually disappeared because of soil erosion (Diamond 2004). However, it is still a matter of debate whether the negative impact of soil erosion on land productivity will impact modern societies (Bakker et al. 2007).

Approximately 80% of the world's agricultural land is subject to moderate or severe erosion (Meliho et al. 2019), and agricultural areas may experience a significant loss of land productivity (LLP) due to erosion. While LLP is c. 0.50% per year in continental Europe (Panagos et al. 2018), the rate in Türkiye is c. 0.92% per year (Aytop & Pınar 2024). The world population of over 8 billion people is expected to surpass 10 billion in the next 80 years (Ritchie 2019). Given that hunger affects 691–783 million people, and over 99% of human food needs are met on land (FAOSTAT 2004, Pimentel & Burgess 2013), it is crucial to protect and enhance the productivity of agricultural areas to secure the food supply. Preservation of agricultural land can be achieved by using the land in an efficient and planned manner according to its capabilities, which is made possible by preparing agricultural land-use plans employing land evaluation methods (Xie et al. 2020, Aytop & Şenol 2022).

Although Türkiye has a rugged topography that is erosion-prone (Duran 2013, Erpul et al. 2018), an understanding of the impacts of improper agricultural practices on erosion is limited. In areas with sloping topography, it is especially vital to integrate erosion mitigation measures into land evaluation methods when preparing land-use plans. Potential impacts of different climate change or land-use planning scenarios have long been simulated (April et al. 2006, Zare et al. 2017, Aytop & Şenol 2022, Pınar & Erpul 2023). These studies have evaluated the possible consequences of changes and led to improved management of natural resources, but it has been difficult to integrate environmental characteristics, economic factors, soil properties and soil conservation practices (contour farming, terracing, etc.) into these methods (Aytop & Şenol 2022). Previous studies have developed land-use scenarios for protecting and increasing the area of agricultural, forest and pasture lands and have examined the soil losses caused by these scenarios (Dymond et al. 2010, Chuenchum et al. 2020, Gong et al. 2022, Nguyen et al. 2023, Patriche 2023). Research that integrates soil conservation practices into land-use planning scenarios has not incorporated any land evaluation methods (Birnholz et al. 2022, Madenoğlu et al. 2024, Vîrghileanu et al. 2024).

In the present study, two soil conservation measures (contour farming and terracing) were integrated into a land evaluation method and erosion-reducing land-use plans for a study area in the Vezirköprü district of Samsun province (Türkiye) that has intensive agricultural activities. The ILSEN quantitative land evaluation method based on the land evaluation criteria of the

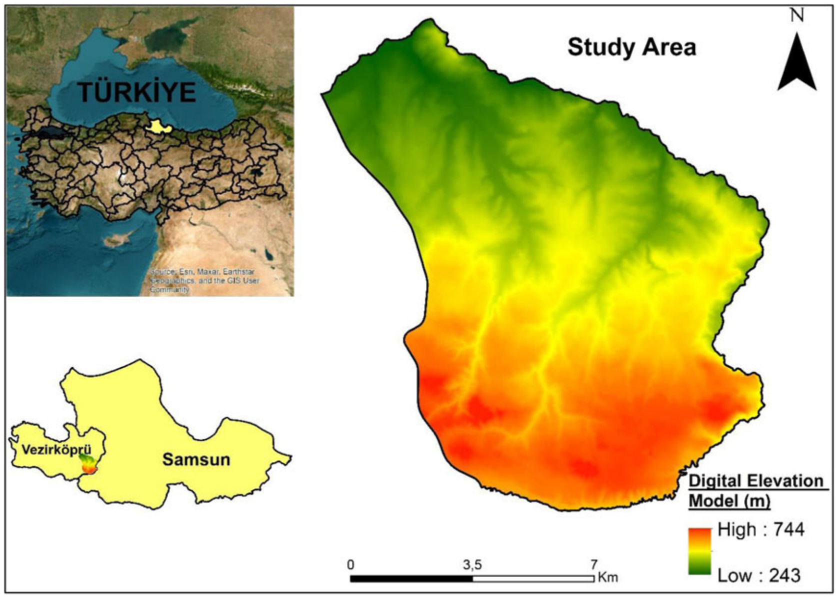

Figure 1. Location map of the study area.

Food and Agriculture Organization (FAO) was developed to be compatible with the ecological conditions of Türkiye (Şenol & Tekeş 1995). A universal empirical soil erosion prediction model that can also be applied in areas with heterogeneous slopes (Wang et al. 2019, Kumar et al. 2022) – the revised universal soil loss equation (RUSLE; Renard et al. 1997) model – was used to determine the effects of these scenarios on soil erosion.

Materials and methods

Study area

The Vezirköprü district of Samsun province in the central Black Sea region of Türkiye (41°2.518′N–35°32.986′E and 41°10.234′N–35°30.087′E; WGS84, Zone-36, UTM-m) covers an area of 111 km^2 ranging from 243 to 744 m above sea level (Fig. 1; Saygın et al. 2023a) and has an average annual precipitation of 527 mm (Uğurlu 2021, Saygın et al. 2023b). It has the humid characteristics of the transition zone between the continental climate type and the humid and temperate climate of the coastal zone; the winter months are colder (January average 2.5°C) and the summer months are hotter (August average 22.3°C) than the coastal zone. The soil moisture regime in the research region was Typic Xeric, while the soil temperature was Mesic (Saygın et al. 2023b).

Database

Soil properties from a digital soil map (Saygın & Dengiz 2023), digital elevation model (DEM) map (http://earthexplorer.usgs.gov) and long-term average precipitation data from the Republic of Türkiye General Directorate of Meteorology were used. Various literature sources were considered to determine the cover management factor (C) values for the scenarios created (Renard et al. 1997, FAO 2000, Marker et al. 2008, Benzer 2010, Panagos et al. 2015b). The existing land-use cover of the study area was identified based on CORINE Land Cover 2018 (https://land.copernicus.eu/en/products/corine-land-cover). The digital soil series map of the study area (Appendix S1, Fig. S1) was used for the K-factor map, and the DEM map of the study area was used for the LS-factor map. The kriging method was also used to prepare the K-factor distribution map. All maps were converted to 10 × 10 m resolution using the *ArcGIS* 10.7.1 program. The methodology of the study is outlined in Appendix S1 (Figs S2 & S3).

Scenarios for land-use planning using the ILSEN model

The land evaluation of the study area was conducted using the ILSEN land evaluation model (Şenol & Tekeş 1995) based on FAO (1977) principles and compatible with the ecological conditions of Türkiye. Nineteen different land-use types (LUTs; Appendix S2, Table S1) that can be cultivated under the ecological conditions of the study area were initially identified and their soil requirements defined based on literature reviews (USDA 1979, Bayraktar 1981, Kün 1983, Perry 1984, Ravina & Magier 1984, Sys et al. 1991, Begg et al. 1998, Sattell et al. 1998, Alonso 2017, Pan et al. 2020, Solaimalai et al. 2020). When applying LUTs involving terracing and contour farming, the slope (%) criterion of the mapping units (MUs) was identified as the primary terrain characteristic; optimal slope values for economically feasible contour farming and terracing practices are 6–10% (FAO 2003) and 12–30% (FAO 2000), respectively. Soil depth was also identified as a key land characteristic, along with slope, for the implementation of terracing practices.

Fifty-eight MUs (bounded areas of land with specific characteristics and mapped from soil, forest and other surveys) and their land characteristics (Appendix S2, Table S2) were obtained from the digital soil map of the study area (Saygın & Dengiz 2023). Land characteristics and MUs were coded and entered into computer software to determine the suitability of LUTs within MUs. A rotation strategy was implemented to cover three seasons in annual crops instead of planting the same crop yearly to ensure the soil and plants were not negatively impacted.

Values of the proportional expected product (PEP) were estimated to assess the limiting effect of land characteristics on LUTs. PEP values were determined by considering the land requirements of LUTs. The PEP value was taken as 1.00 if a certain level of any land characteristic (Appendix S2, Table S2) did not restrict the cultivation of the LUT in any way and as 0.00 if it made it impossible (Appendix S2, Table S3).

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In the final stage of the land evaluation process, physical mapping unit indices (PMUIs) were calculated to indicate the suitability of the MUs for the LUT, and mapping unit indices (MUIs) were determined by multiplying the PMUIs by the profitability index (PI) values of the LUTs by using Directorate of Agriculture and Forestry of Samsun province cost and income data of LUTs. PI data for some products not cultivated in the region were unavailable, and the PI values for some LUTs could not then be calculated.

Following the land evaluation, five different land-use planning scenarios were developed (Appendix S2, Table S4). The current land use of the research area (CORINE 2018) was defined as Scenario 1. Scenarios 2 and 3 were determined by selecting the highest MUI and PMUI values of the MUs. Scenario 4 was created by prioritizing soil-protected LUTs within PMUI values for which the suitability value was higher than 0.50 (FAO, 1977). Scenario 5 was created for each MU by prioritizing non-agricultural use (LUT18 and LUT19) areas with suitability values higher than 0.50.

Soil loss evaluation

The RUSLE method (Renard et al. 1997, Deumlich et al. 2005, Gutzler et al. 2015) was utilized to predict erosion rates for the five land-use planning scenarios. Equation 1 was used to estimate average annual soil loss measured as t ha^{-1} year^{-1} based on soil erodibility (K), rainfall erosivity (R), cover management (C), topography (LS) and support practices (P) on erosion (Renard et al. 1997). GIS techniques and *ArcGIS* 10.7.1 software were used to calculate factor layers and to generate erosion risk in five classes: very low (0–1 t ha^{-1} year^{-1}), low (1–5 t ha^{-1} year^{-1}), moderate (5–10 t ha^{-1} year^{-1}), high (10–20 t ha^{-1} year^{-1}) and very high (≥20 t ha^{-1} year^{-1}; Erpul et al. 2018, Aytop & Pınar 2024).

$$A = (R) \times (K) \times (LS) \times (C) \times (P) \tag{1}$$

Rainfall erosivity (R)

Data collected from the nearest rainfall station in Vezirköprü district were used to compute R (MJ mm ha^{-1} h^{-1} year^{-1}; Equation 2). Due to the station lacking high-resolution rainfall records, the Modified Fournier Index (MFI) equation (Arnoldus 1980) was employed to calculate it (Equation 3).

$$R = (4.17 \times MFI) - 152 \tag{2}$$

$$MFI = \sum\nolimits_{i=1}^{12} Pi^2/P \tag{3}$$

where *Pi* is the average precipitation in month *i* (mm) and *P* is the average precipitation (mm year^{-1}).

To integrate the R value for the Vezirköprü station into the study area, it was assumed that for every 100-m increase in elevation, annual precipitation increases by 54 mm (Schreiber 1904). Using the slope map, the R value map of the study area was created (Equation 4).

$$R_{location} = R_{station}(P_{location}/P_{station}) \tag{4}$$

where $R_{location}$ is the R value calculated for every 100-m change in the study area, $R_{station}$ is the R value calculated for the Vezirköprü station, $P_{location}$ is precipitation re-calculated for every 100-m increase in elevation in the study area and $P_{station}$ is the precipitation for the Vezirköprü station (mm year^{-1}).

Soil erodibility (K)

The soil erodibility parameter K, measuring the soil's resistance to raindrops' erosive properties (Wischmeier & Smith 1978), which ranges from 0 to 1, was derived from the analysis of structure type, organic matter, hydraulic conductivity and soil texture of the soils obtained from the digital soil map of the study area (Equation 5; Saygın & Dengiz 2023).

$$100 \times K = ((2.1 \times 10^{-4})M^{1.14} \times (12 - OM) + 2.5 \times (c - 3) + (3.25 \times (b-2))/d \tag{5}$$

where *M*, *OM*, *c*, *b* and *d* are the particle size, organic matter content (%), water permeability code, structure type code and conversion coefficient to metric (7.59), respectively. *M* was calculated as per Equation 6:

$$M = (\%silt + \%veryfinesand) \times (100 - \%clay) \tag{6}$$

Slope length and steepness (LS)

Estimation of the LS factor – the ratio of soil loss in an area 22.13 m long with a 9% slope to that in another location with the same conditions, and which is among the most critical factors regarding the rate of water-induced soil erosion (Bircher et al. 2019, Kumar et al. 2022) – used the equation of Moore and Burch (1986). Since the resolution of the DEM map of the study area is 10 m × 10 m, the cell size was considered to be 10 m in the LS-factor calculation (Equation 7):

$$LS = \left(\frac{\text{Flow Accumulation} \times \text{ Cell Size}}{22.13}\right)0.4 \times \left(\frac{SinSlope}{0.0896}\right) \wedge 1.3 \tag{7}$$

Cover management factor (C)

Values of the C factor – the ratio of erosion on vacant land to that on land under agricultural activity (Wischmeier & Smith 1978) and related to vegetation cover and production techniques (Zare et al. 2017) – were assigned based on the literature (Appendix S2, Table S5).

Conservation practice (P)

The unitless P-factor values were derived from the literature review; they were set at 1 for land uses that do not include soil conservation measures (Renard et al. 1997). In contrast, for land uses that include practices such as terracing and contour farming, these values were taken as 0.2 and 0.5, respectively (Wischmeier & Smith 1978).

Study limitations

The main limitations of this study are that the amount of tolerable soil loss (T; t ha^{-1} year^{-1}) was not calculated, and no field validation of the erosion calculations was carried out. T can be calculated or determined by referring to different studies. We aimed to include soil conservation practices as a LUT in the ILSEN model; we considered slope percentages as recommended by the FAO for

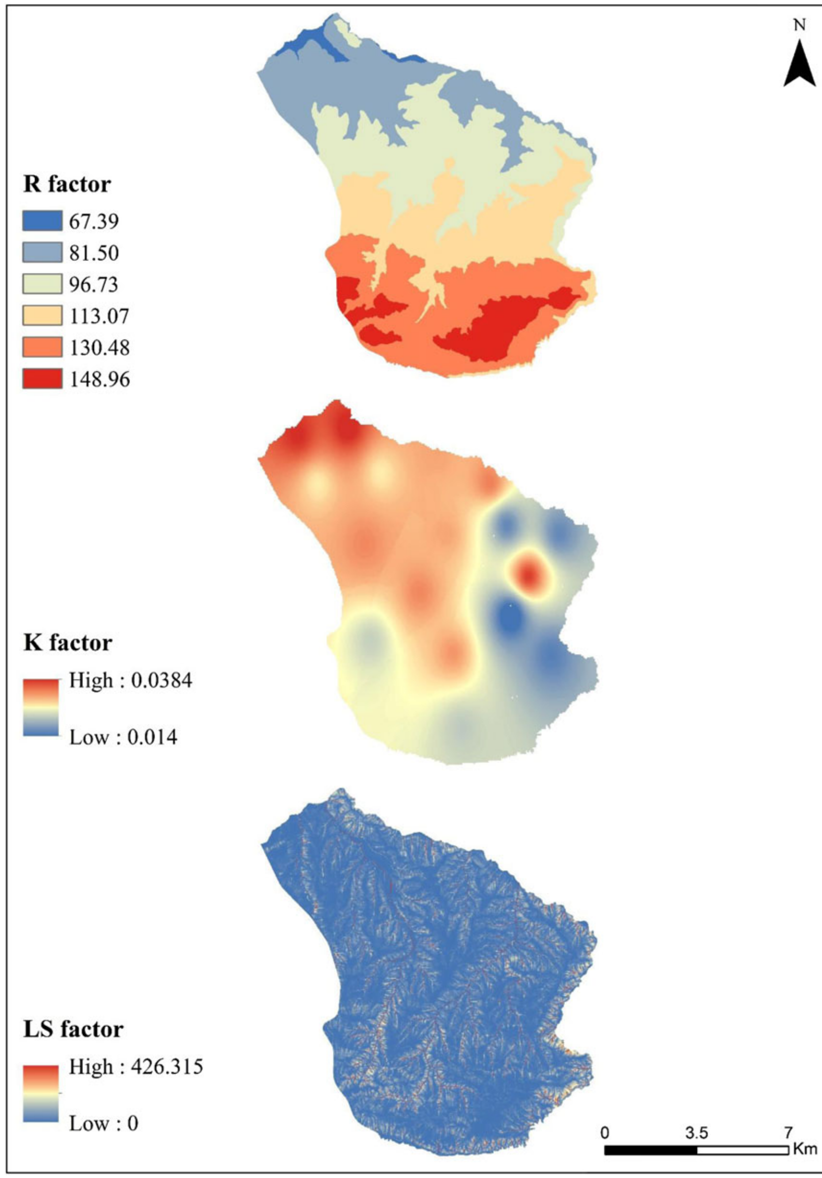

Figure 2. Map of R (MJ mm ha^{-1} h^{-1} $year^{-1}$), K (t ha h ha^{-1} MJ^{-1} mm^{-1}) and LS factors (unitless) of the study area.

these practices. The RUSLE was only used to check whether land-use planning reduced erosion and to estimate soil losses.

Results

Scenarios for land-use planning

Scenario 1 (current land use) had the largest agricultural areas (8108 ha). Forest and pasture areas covered 1311 and 1117 ha, respectively (Appendix S2, Table S6). While the content of the other four scenarios varied, the LUTs with the largest surface area were contour-cultivated annual crops (Appendix S2, Table S6). The average slope of the study area was close to the 10% recommended by FAO (2003) for contour farming, so contour farming practices were expected to be intensive in the scenarios.

In Scenario 2, the wheat and sunflower rotation (contour farming) had the greatest area (48.59%), followed by LUT17 (19.83%), LUT18 (11.47%), LUT19 (10.98%) and LUT16 (8.23%). The PMIU scenario with economic analysis had 4.87% more terraced orchard area compared to the MUI scenario. These greater terraced orchard areas resulted from prioritizing profitability in the PMIU scenario. In Scenario 4, LUTs including terrace and contour agriculture had the largest land area (95.56%) because of the focus on soil conservation practices. Scenario 5 (prioritizing non-agricultural areas) had the greatest forest and pasture area (34.96%), followed by Scenario 2 (22.45%), Scenario 3 (10.58%) and Scenario 4 (4.44%; Appendix S2, Table S6).

RUSLE model of the scenarios

The R-factor values varied between 67.39 and 148.96 MJ mm ha^{-1} h^{-1} $year^{-1}$, depending on altitude (Fig. 2). Assuming that precipitation increased with altitude, the soil erodibility K factor ranged from 0.0384 to 0.014 t ha h ha^{-1} MJ^{-1} mm^{-1}; it was greater in the north and north-west of the study area than elsewhere (Fig. 2).

This suggests that the soil series in the eastern and southern regions of the study area were more resistant to the erosive properties of rainfall. The LS factor ranged from 0 to 426.315 for the study area, with the lowest values occurring in flat and nearly flat alluvial areas, while the highest LS-factor values were observed

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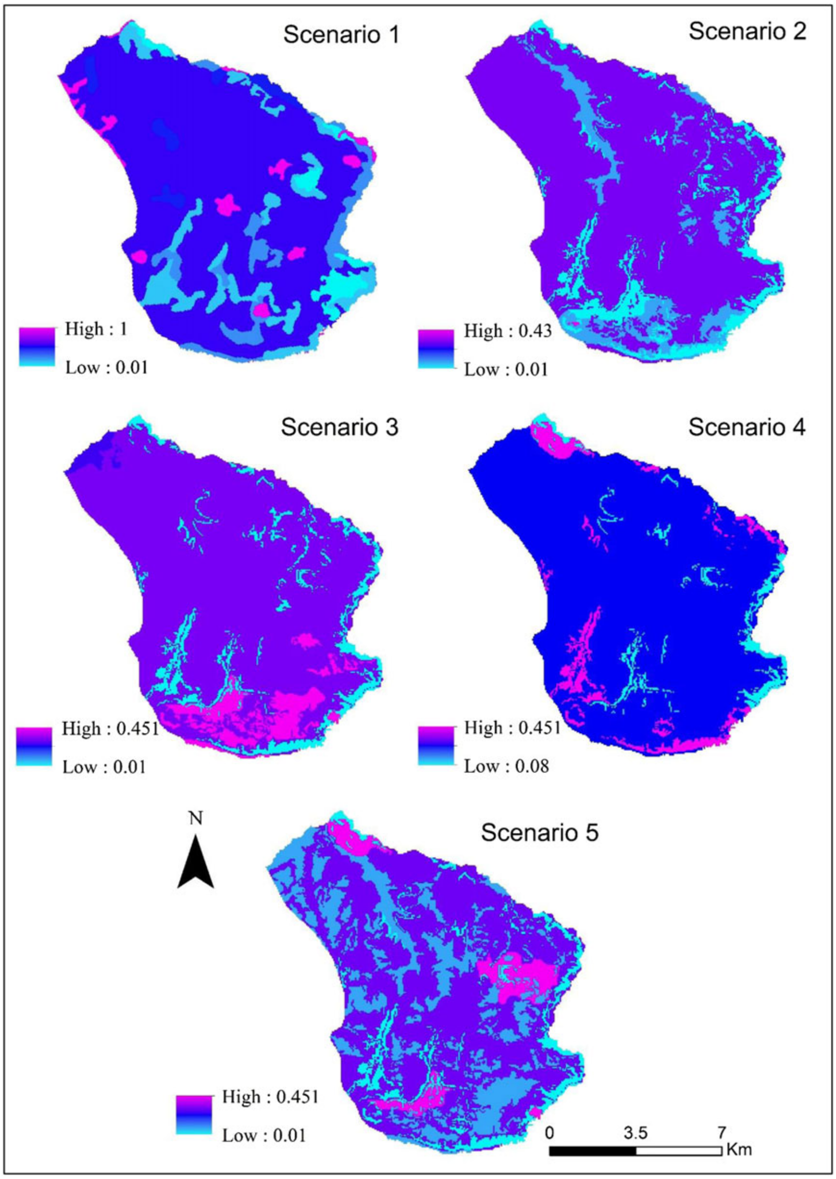

Figure 3. C-factor maps of the scenarios.

in areas with steep slopes, such as along rivers. The spatial distribution of C-factor values varied according to the land-use content of the scenarios. Scenario 5, with denser forest and pasture areas, had the lowest average C factor (0.16), while, as expected, scenarios with more intensive agricultural LUTs had higher C-factor values (Fig. 3).

Since there were no soil conservation practices in the study area at the time, Scenario 1's mean P-factor value was 1.00. The average P values for Scenarios 1–5 were 1.00, 0.74, 0.77, 0.45 and 0.89, respectively (Fig. 4).

Soil losses in the scenarios

Scenario 5, which involved non-agricultural practices, had the lowest average soil loss (Fig. 5) and average C-factor value (0.16), and thus the lowest soil loss. Scenario 1 (current land use of the basin) had the highest average soil loss, with an average C-factor value of 0.43.

The four scenarios based on the ILSEN method had significantly lower average erosion rates compared to Scenario 1 (Fig. 5).

Scenario 2, with the lowest C-factor value after Scenario 5, had an average annual soil loss of 0.97 t ha^{-1} $year^{-1}$, and it did not consider the economic returns of LUTs (Fig. 6). This scenario's average C-factor value was 0.19, the second lowest after Scenario 5. Despite this, Scenario 2 resulted in less estimated soil loss than Scenario 3 (Fig. 5).

Soil conservation practices also impact the erosion risk classes in the study area. Areas with more than 20 t of soil loss per year were significantly reduced in the other scenarios compared to Scenario 1 (Appendix S2, Table S7). In Scenario 1, 47.76% of the study area was under low erosion risk, while in the other scenarios prepared using the ILSEN land evaluation method, this risk was present in greater than 80% of the study area, except for in Scenario 3. In Scenario 3, this risk was present in 70.21% of the study area (Appendix S2, Table S7).

Discussion

The created scenarios had significantly lower soil erosion compared to the current land use in Vezirköprü district

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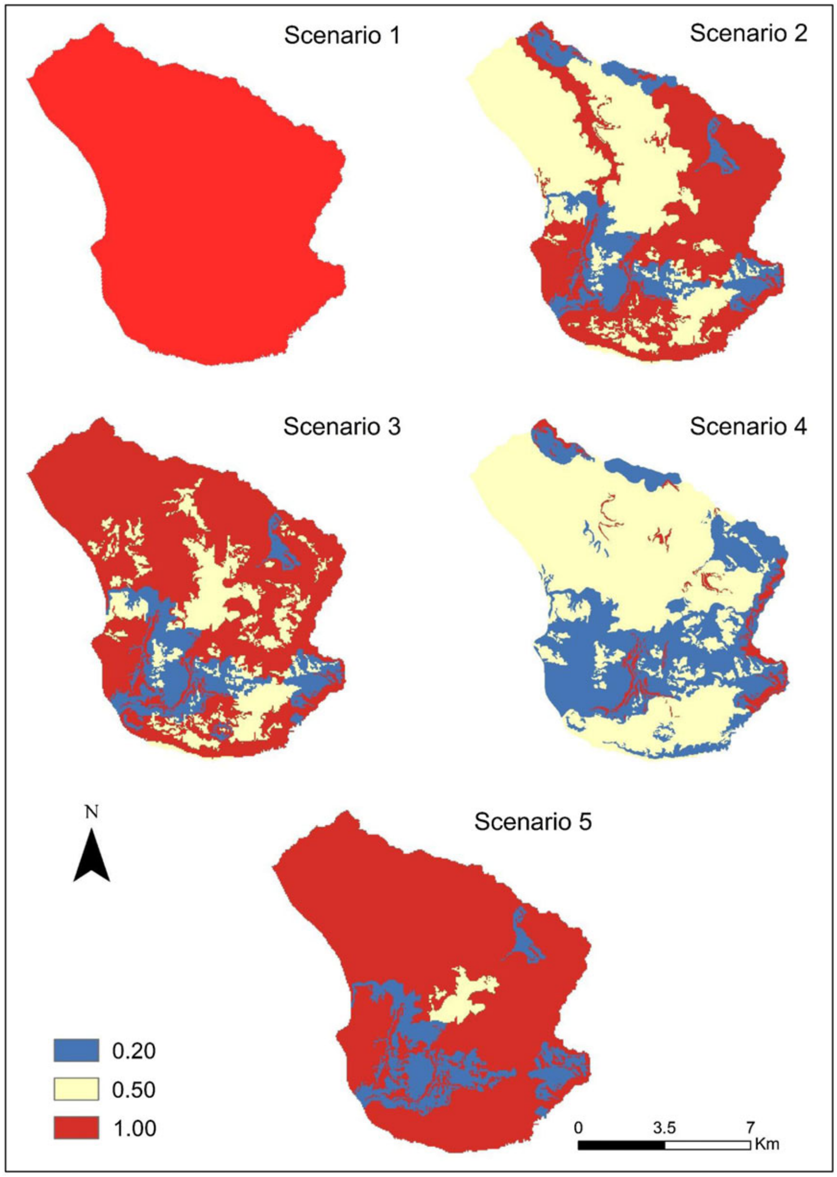

Figure 4. P-factor maps of the scenarios.

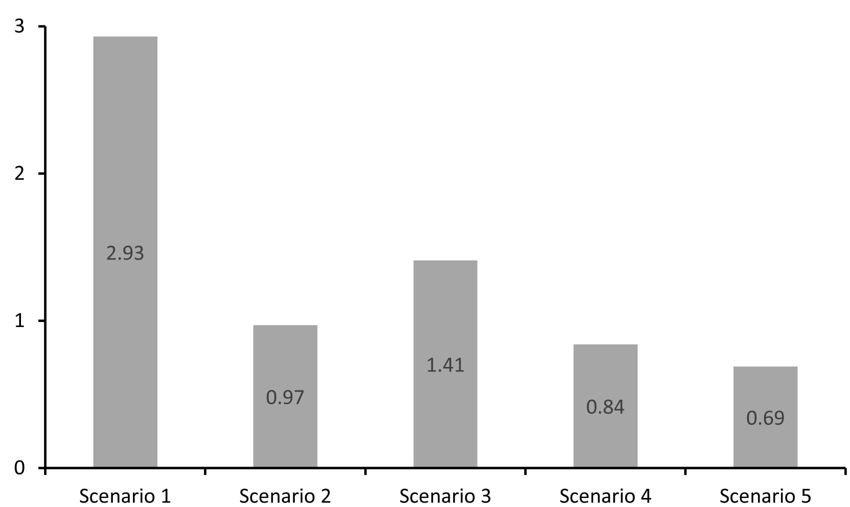

Figure 5. Average soil loss (t ha^{-1} $year^{-1}$) in the scenarios.

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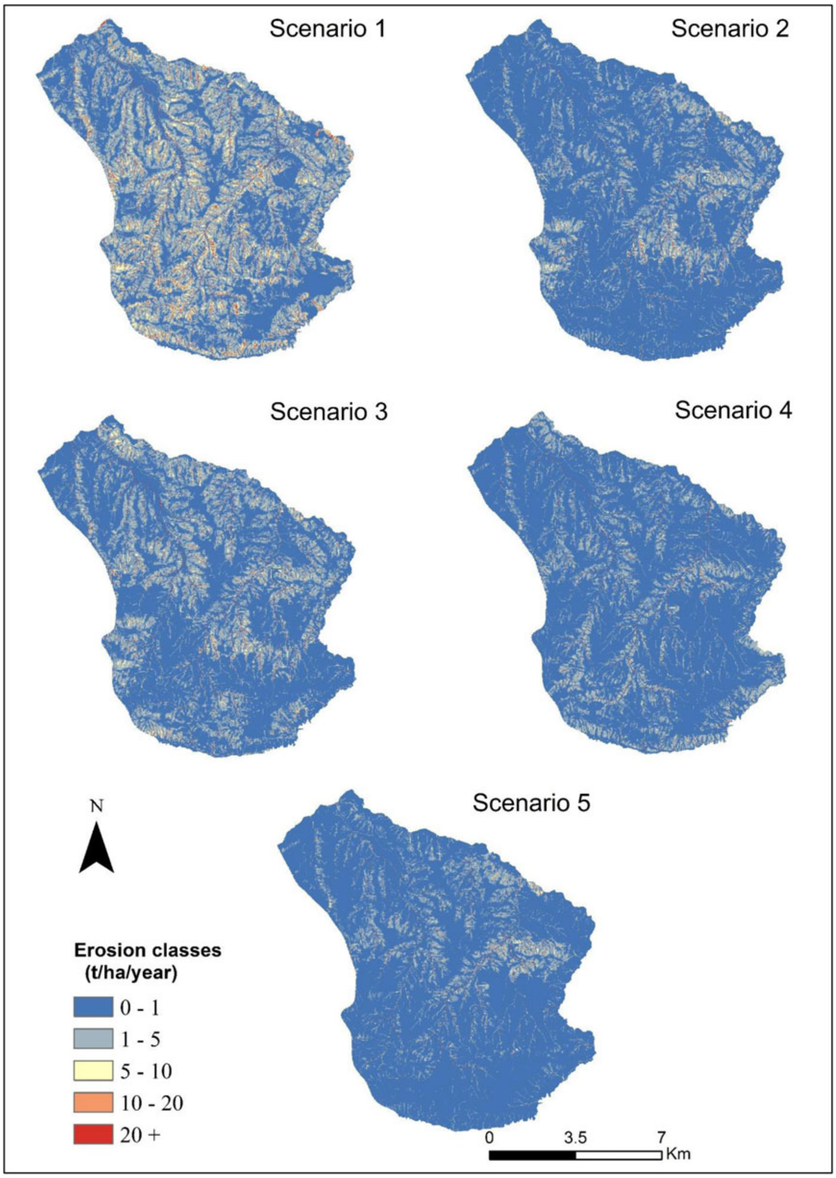

Figure 6. Spatial distribution of average annual soil loss in the scenarios.

(Scenario 1). Although all factors influence erosion to some extent in RUSLE, the LS and C factors were the most influential on soil loss (Risse et al. 1993, Panagos et al. 2015a). In the present study, the LS, K and R factors had equal values in all scenarios, while the P-factor average of Scenario 5, which had the lowest erosion rate, was greatest, with a value of 0.89. In contrast, the C-factor average had the lowest value (0.16) among the scenarios; it was therefore more effective for determining differences in the rate of soil loss between scenarios, and it indicated significantly reduced soil erosion. This corroborates previous studies (El Jazouli 2017, Azimi et al. 2019) demonstrating that the C factor can increase or decrease soil erosion by up to 1000-fold (0.001 versus 1; Tsai et al. 2021, Moisa et al. 2023, Sathiyamurthi et al. 2023). The difference in C-factor averages between the scenarios was related to the fact that forest and pasture areas covered more area in Scenario 5 (c. 34.96% of the area) than in the other scenarios (Appendix S2, Table S6). Although increasing non-agricultural areas in these scenarios might be the most effective and economical solution to reduce soil erosion, the acceptability of this approach to farmers who make their livings from the land they live on will be very low. In sloping areas, scenarios that include soil conservation practices will be more acceptable to farmers.

Similarly, the C factor most influenced the differences in soil loss among Scenarios 2, 3, 4 and 5. For instance, the higher amount of soil loss in Scenario 3 (1.41 t ha^{-1} $year^{-1}$) compared to Scenario 2 (0.97 t ha^{-1} $year^{-1}$) can be explained by prioritizing the profitability of LUTs, because orchards, which are more profitable (Badiu et al. 2015, Lordan et al. 2019, Nieto et al. 2023), have higher C-factor values than annual crops. Horticultural crops such as walnuts, grapes and almonds require higher capital inputs than annual field crops but yield relatively higher profits for farmers (Wolz & DeLucia 2019, De Leijster et al. 2020, Aytop & Şenol 2022). As the mean C-factor values increased in the scenarios in which orchards occupied most of the area, soil erosion rates were also greater.

Adding soil conservation practices to the scenarios also changed the average P-factor values of agricultural plans and

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reduced the rates of soil loss. Similarly, Thomas et al. (2018) and Islam et al. (2020) reported that soil conservation practices significantly reduced severe erosion rates.

Scenario 4 had the lowest soil loss (0.84 t ha^{-1} $year^{-1}$) among all scenarios after Scenario 5; this scenario was specifically designed for agricultural purposes, incorporating terrace and contour farming techniques, resulting in the lowest average P-factor value. Soil conservation practices such as contour farming and terracing play a crucial role in reducing soil erosion rates (Ricci et al. 2020, Didoné et al. 2021, Rutebuka et al. 2021, Saggau et al. 2023) and in preserving soil organic matter (Do et al. 2023). Tang et al. (2015) reported that terracing in particular positively changed erosion classes in the Loess Plateau of China. Similarly, land-use planning scenarios that include soil conservation practices reduced soil losses by c. 79% compared to current land use (Aytop & Şenol 2022). Because of the high cost of terracing on sloping land (e.g., in Kenya; Mcharo & Maghenda 2021), LUTs with a high profit return should be selected for terracing. The profitability of LUTs is related a region's climatic conditions, soil characteristics, location, people's preferences and many other factors. Compared to the long-term costs of soil erosion, which are not just agricultural but also include off-site impacts such as pollution and filling of dams (Colombo et al 2005, Borrelli et al. 2017), those of soil conservation practices are insignificant. Globally, the cost of soil erosion is USD 400 billion annually (FAO 2016).

Our study supports the effectiveness of soil conservation practices for reducing erosion rates, and it could serve as a model for evaluating soil erosion risks in agricultural, forest and pasture areas more generally. In our case, the C factor was more effective for reducing soil erosion than the support application factor. The effect of the P factor on erosion can be increased by integrating different soil protection practices into the model (Aytop & Şenol 2022).

Conclusion

We have shown that soil conservation added to the ILSEN method significantly reduced soil erosion in LUTs; it also reduced the current erosion rate of the study area in scenarios in which C-factor values varied. Scenario 5, in which forest and pasture areas were kept dense, had the lowest soil loss rate. This proves that the C factor is one of the most critical factors for reducing erosion, along with the LS factor.

Our approach has significant potential for application in high-slope geographies elsewhere where farmers' primary source of livelihood is agriculture. Since the initial costs of soil conservation practices such as terracing are high, it will be difficult for farmers to establish these practices; thus, public investments are necessary. The cultivation of LUTs determined according to the land evaluation method is vital for soil sustainability, so farmers and public institutions should cooperate closely; only then will the protection of agricultural production and the productivity of the lands involved be ensured.

Supplementary material. To view supplementary material for this manuscript, please visit https://doi.org/10.1017/S0376892924000298.

Data availability. The datasets generated and analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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Author contributions. FS: Writing the original draft of the manuscript, reviewing and editing; HA: Writing the original manuscript draft, reviewing, editing, calculating, creating maps and corresponding; OD: Writing the original draft of the manuscript, reviewing and editing.

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Competing interests. The authors declare that they have no competing interests related to the content of this manuscript. The authors have no relevant financial or non-financial interests to disclose.

Ethical standards. Not applicable.

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