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Integrated soil-terrain assessment of agricultural land capability and suitability in mountainous environment

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Abstract

Mountainous terrain imposes major constraints on agricultural land use by increasing erosion risk and limiting cultivation potential. This study assessed agricultural land capability and suitability in Kamenica Municipality, eastern Kosovo, using an integrated framework combining soil survey, World Reference Base (WRB) classification, GIS-derived terrain analysis, standardized land capability classification, FAO-based land suitability evaluation, and multivariate statistical analysis. A total of 135 representative soil profiles were described and analyzed, with particular emphasis on slope gradient and effective soil depth as the principal limiting factors. Luvisols, Cambisols, and Umbrisols together cover 83.1% of the municipality. However, agricultural potential is strongly constrained by terrain morphology: Classes VI-VII account for 46.9% of the area, whereas high-capability land (Classes I-II) occupies only 4.5%. Suitability analysis further shows that 58.6% of the land is not suitable for rainfed crops and 84.7% is not suitable for irrigated crops, while grazing displays the broadest suitability, with 51.8% of the area classified as moderately suitable. These findings indicate that agricultural planning in mountainous regions should prioritize land uses compatible with terrain and soil limitations, particularly extensive grazing and conservation-oriented management.

Keywords: Luvisols, Cambisols, Rainfed crops

Introduction

Agricultural land systems worldwide are increasingly affected by land degradation driven by demographic pressure, climate variability, and unsustainable land management. These pressures are particularly severe in mountainous and hilly regions, where steep slopes, shallow soils, and high erosion susceptibility restrict land-use options and increase environmental vulnerability. Under such conditions, inappropriate land use can accelerate soil degradation, reduce agricultural productivity, and destabilize ecosystem functioning (Moore *et al*., 1993; Florinsky *et al*., 2002; Lal, 2003; García-Ruiz *et al*., 2013; Lal, 2015; Panagos *et al*., 2015 and Borrelli *et al*., 2017). In these landscapes, sustainable agricultural planning requires land-evaluation approaches that consider not only soil properties but also terrain-related constraints.

The conceptual foundation of land evaluation was established by the FAO framework and subsequently refined for rainfed, irrigated, and grazing land-use systems (FAO, 1976, 1983, 1985, 1991). Later methodological developments further emphasized the systematic matching of land characteristics with land-use requirements and provided structured approaches for evaluating physical limitations to agricultural use (Klingebiel and Montgomery, 1961, Sys *et al*., 1991; Rossiter, 1996). These frameworks remain central to agricultural land assessment, especially in environments where slope, erosion risk, and soil depth impose strong limitations.

More recently, land evaluation has increasingly incorporated geographic information systems, digital terrain analysis, and spatial decision-support methods. These developments have improved the integration of soil survey data, digital elevation information, land cover, and environmental constraints within spatially explicit analytical frameworks for agricultural planning (Tarboton, 1997; Burrough and McDonnell, 1998; Malczewski, 1999; Wilson and Gallant, 2000; Florinsky, 2012; Hengl *et al*., 2017). Advances in digital soil mapping have further strengthened the representation of soil variability and its relevance for agricultural planning (McBratney *et al*., 2003; Minasny and McBratney, 2016). Recent European policy-oriented research has also highlighted those healthy soils

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are not only essential for environmental sustainability but also a strategic asset for agricultural resilience, land productivity, and broader EU competitiveness (Panagos *et al*., 2025). This broader context strengthens the need for robust, spatially explicit soil–terrain assessment.

Among terrain-related controls, slope gradient is widely recognized as a dominant factor because it directly influences runoff generation, erosion intensity, accessibility, and mechanization feasibility. Empirical and process-based studies show that soil loss increases nonlinearly with slope steepness, and such threshold responses are especially pronounced in mountainous landscapes (Wischmeier and Smith, 1978; Moore *et al*., 1993; Montgomery and Dietrich, 1994; Renard *et al*., 1997; Nearing, 2001). Effective soil depth represents a second key control because it regulates rooting volume and water-storage capacity, yet in steep terrain it is frequently reduced by long-term erosion and slope instability (Van Oost *et al*., 2007; Bockheim *et al*., 2014; Sauer *et al*., 2018). As a result, intensive cropping systems are often poorly matched to mountainous terrain, whereas more extensive systems, particularly grazing, are generally more compatible with shallow soils and steep slopes (Blum, 2007; Akinci *et al*., 2013; Zolekar and Bhagat, 2015; Keesstra *et al*., 2016).

The integration of GIS into land evaluation has substantially improved the ability to analyze soil–terrain relationships and to produce spatially explicit assessments of land capability and suitability. Such approaches facilitate the identification of constraint zones, the visualization of land potential, and the evaluation of alternative land-use options. Multivariate statistical techniques further support this process by quantifying the relative importance of controlling factors and clarifying interactions among soil and terrain variables. Together, these tools provide a stronger analytical basis for land-use planning in environmentally constrained landscapes.

Despite these methodological advances, integrated land-evaluation studies remain limited in mountainous regions of Southeastern Europe. These areas are characterized by complex relief, diverse soil resources, and persistent land-use pressures, yet planning is often constrained by limited spatial data and fragmented evaluation frameworks. As a result, land-use decisions may fail to reflect inherent land limitations, increasing the risk of land degradation and inefficient resource use. In this context, Kamenica Municipality in eastern Kosovo provides a representative case for examining how soil resources, terrain constraints, and land-use requirements interact at the municipal scale. The present study addresses this gap through an integrated assessment of agricultural land capability and land suitability based on detailed soil survey data classified according to the World Reference Base (WRB), GIS-derived terrain attributes, standardized land capability classification, FAO-based land suitability evaluation, and multivariate statistical analysis.

The objectives of this study are: (i) to characterize the spatial distribution of soil resources; (ii) to assess agricultural land capability in relation to terrain constraints; (iii) to evaluate land suitability for different agricultural land uses; and (iv) to synthesize these results within an integrated analytical framework. In doing so, the study aims to contribute to the scientific understanding of land evaluation in mountainous landscapes and to support sustainable land-use planning and soil-conservation strategies in regions facing similar environmental challenges.

Materials and Methods

Study area and Environmental setting

The study was conducted in Kamenica Municipality, located in eastern Kosovo (Fig. 1), an area characterized by complex mountainous terrain and pronounced spatial variation in elevation, slope gradient, and landform structure. The municipality covers approximately 41,580 ha and includes a heterogeneous landscape composed of alluvial valley bottoms, gently undulating foothills, and steep mountain slopes.

Figure 1: Geographic position of Kamenica Municipality

This relief complexity generates strong local variation in microclimatic conditions, vegetation cover, and soil-forming processes, resulting in highly heterogeneous land resources. The climate is predominantly continental, with moderate Mediterranean influence and is characterized by cold winters and warm summers. Precipitation is unevenly distributed during the year, with higher amounts typically occurring in spring and autumn, periods that also coincide with increased runoff and erosion risk. In combination with rugged relief, these climatic conditions exert a strong influence on soil development, drainage behavior, and land degradation processes.

Natural vegetation ranges from grasslands and shrublands in lower terrain positions to forest ecosystems at higher elevations, whereas agricultural land use is concentrated mainly in valley floors and on lower slopes. The interaction between steep terrain, variable parent materials, and mixed land use makes the municipality representative of mountainous agricultural landscapes in Southeastern Europe, where land-use planning must reconcile production needs with strong physical and environmental constraints (Panagos *et al*., 2025).

Soil survey, spatial data, and GIS-based analysis

A detailed soil survey was conducted to characterize soil resources and support spatial land evaluation in Kamenica Municipality. A total of 135 representative soil profiles were described and sampled across the municipality, covering a broad range of geomorphic positions, land-use types, and elevation zones. Soil profile descriptions followed internationally accepted field-survey procedures and included horizon depth, color, texture, structure, stoniness, drainage conditions, and evidence of erosion or deposition.

Laboratory analyses were carried out to determine key soil properties relevant to soil classification and land evaluation, including particle-size distribution and soil organic carbon content. Soils were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015), ensuring international comparability and consistency. The classified profiles formed the basis for the delineation of soil mapping units.

Geographic information systems were used to integrate soil survey data with terrain attributes and land-cover information. A digital elevation model (DEM) with a spatial resolution of 5m was used to derive slope gradient and other terrain parameters relevant to agricultural land evaluation. Slope was calculated using standard GIS procedures and subsequently grouped into slope classes representing increasing levels of agricultural constraint. Because DEM-derived terrain variables are sensitive to spatial resolution and input-data quality, the results should be interpreted as a municipality-scale assessment rather than a parcel-scale prediction.

Soil profile locations were georeferenced and integrated into the GIS environment. Soil mapping units were delineated by combining field observations, terrain attributes, and land-cover patterns through expert interpretation supported by spatial analysis. This procedure enabled the production of a spatially explicit soil map consistent with both pedological observations and geomorphic context. Slope length-steepness relationships were interpreted according to established erosion-modelling frameworks (Desmet and Govers, 1996; Renard *et al*., 1997), while flow-routing and terrain-curvature analyses were based on the approaches described by Tarboton (1997) and Wilson and Gallant (2000).

Land capability and land suitability assessment

Agricultural land capability was assessed using the PTB land capability classification system, which evaluates the inherent suitability of land for agricultural use based on permanent physical constraints. In this study, the assessment focused on slope gradient, effective soil depth, stoniness, and erosion susceptibility. Each spatial unit was evaluated against the PTB criteria and assigned to one of seven capability classes, ranging from high capability (Classes I-II) to very low capability (Class VII).

Land suitability was then assessed for specific agricultural land uses, namely rainfed crops, irrigated crops, perennial crops, and grazing systems. The evaluation followed FAO land-evaluation principles, which are based on matching land characteristics with the requirements of particular land uses. For each land-use type, slope gradient, effective soil depth, drainage conditions, and erosion risk were considered as the principal limiting factors. Suitability was classified into four categories: highly suitable, moderately suitable, marginally suitable, and not suitable.

The land-suitability assessment extends the capability classification by incorporating land-use-specific requirements rather than relying only on the inherent physical condition of the land.

Statistical analysis and methodological integration

Statistical analyses were performed to quantify relationships among soil properties, terrain attributes, and land-evaluation outcomes. Descriptive statistics were calculated for slope gradient, effective soil depth, and soil organic carbon across land capability classes. Bivariate analyses were used to examine the relationships between slope gradient and land capability, and between slope gradient and effective soil depth. In addition, multivariate correlation analysis was conducted to assess the relative importance and interaction of the main controlling variables, including slope gradient, soil depth, soil organic carbon, and the land capability index. These analyses provided quantitative support for identifying dominant limiting factors and for confirming patterns observed in the spatial land-evaluation results.

The methodological framework applied in this study integrates soil survey, GIS-based terrain analysis, land capability classification, land suitability assessment, and statistical analysis within a single workflow. By combining pedological observations with terrain-derived variables and land-use-specific evaluation criteria, the framework provides a transparent and spatially explicit basis for assessing agricultural potential in mountainous terrain. Because it relies on established methods, internationally recognized classification systems, and widely available spatial data, the approach is reproducible and transferable to other mountainous regions with similar environmental constraints (De la Rosa *et al*., 2004; Hengl *et al*., 2017).

Results

Spatial distribution and quantitative dominance of soil resources

The soil survey, integrated with GIS-based spatial analysis, identified eight World Reference Base (WRB) Reference Soil Groups within Kamenica Municipality, indicating pronounced pedological heterogeneity across the study area. This variability is mainly related to relief differentiation, lithological diversity, slope-gradient contrasts, and land-cover distribution. In mountainous environments, strong altitudinal gradients and irregular topography create marked differences in microclimate, drainage conditions, and erosion intensity, which in turn influence soil formation processes. As a result, soil-forming factors interact over short spatial distances and produce rapid transitions in soil morphology and physicochemical properties (Florinsky *et al*., 2002; Bockheim and Hartemink, 2017). This pattern is consistent with the heterogeneous soil distribution typically observed in complex mountain landscapes.

Although eight Reference Soil Groups were identified, the soil cover is quantitatively dominated by three groups, namely Luvisols, Cambisols, and Umbrisols, which together occupy 83.1% of the municipal territory (Table 1). Luvisols are mainly associated with relatively stable landscape positions and moderately developed profiles, Cambisols reflect intermediate stages of pedogenesis under variable relief conditions, and Umbrisols occur predominantly in higher-elevation zones characterized by increased organic matter accumulation. The predominance of these three groups shows that, despite marked local variability, soil development across the municipality is concentrated within a limited number of major pedogenic environments shaped by relief and parent material.

Table 1: Distribution of WRB soil groups in Kamenica Municipality

Soil group	Area (ha)	Share (%)	No. of profiles (n)
Luvisols	12 250	29.5	38
Cambisols	11 360	27.3	35
Umbrisols	10 900	26.3	33
Phaeozems	3 680	8.9	12
Regosols	2 420	5.8	10
Vertisols	230	0.6	2
Kastanozems	460	1.1	3
Leptosols	280	0.5	2
Total	**41 580**	**100.0**	**135**

Luvisols represent the most extensive soil group, covering 12,250 ha or 29.5% of the study area, and are represented by 38 soil profiles. Their spatial distribution is concentrated in valley bottoms, lower slope positions, and gently undulating terrain, where relatively stable geomorphic conditions have favored clay translocation and profile differentiation. Their dominance is therefore associated with areas where pedogenesis has proceeded under comparatively moderate erosion pressure and adequate moisture availability, conditions commonly linked with Luvisol formation in temperate landscapes (IUSS Working Group WRB, 2015; Sauer *et al*., 2018).

Cambisols occupy 11,360 ha or 27.3% of the municipal area and are represented by 35 soil profiles. They are widely distributed across middle-slope positions and indicate active but incomplete soil development under conditions of moderate relief energy and continuing geomorphic adjustment. In such settings, weathering and horizon differentiation are present but remain moderated by erosion and sediment redistribution, making Cambisols characteristic of transitional slope environments in hilly and mountainous terrain (Várallyay, 2010; Hengl *et al*., 2017).

Umbrisols cover 10,900 ha or 26.3% of the municipality and are represented by 33 soil profiles. They occur predominantly at higher elevations and in areas under permanent vegetation cover, including grasslands and forests. Their distribution is associated with enhanced organic matter accumulation under cooler and more humid microclimatic conditions, together with lower anthropogenic disturbance. Similar relationships between Umbrisols, elevation, and vegetation stability have been reported for mountainous regions of Central and Southeastern Europe (Dazzi *et al*., 2014; Zádorová *et al*., 2015).

Secondary soil groups occupy smaller but pedologically important portions of the landscape. Phaeozems account for 3,680 ha or 8.9% of the area and are concentrated mainly in valley floors and depositional environments with deeper profiles, higher base saturation, and more favorable moisture conditions. Regosols cover 2,420 ha or 5.8% and occur almost exclusively on steep, erosion-prone slopes, where soil formation is repeatedly interrupted by surface erosion and mass movement. This distribution is consistent with the general association of Regosols with young, weakly developed soils in dynamic geomorphic settings (Bockheim *et al*., 2014). Vertisols, Kastanozems, and Leptosols together account for less than 3% of the total municipal area and are confined to localized geomorphic or hydrological settings. Their limited extent suggests that the environmental conditions required for their broader development are not widespread within the municipality.

Figure 2 illustrates the spatial distribution of the WRB soil groups across Kamenica Municipality and confirms the areal predominance of Luvisols, Cambisols, and Umbrisols within the local soil cover.

Agricultural land capability structure and class dominance

Quantitative results of the agricultural land capability classification are presented in Table 2, which summarizes the spatial extent of each PTB capability class together with the corresponding mean slope gradient and mean effective soil depth. A clear numerical gradient is evident across the capability sequence. From Classes I-II to Class VII, mean slope increases from 3.2% to 48.5%, whereas mean effective soil depth declines from 128 cm to 29 cm. This

Table 2: Agricultural land capability classes and terrain characteristics

PTB class	Area (ha)	Share (%)	Mean slope (%)	Mean soil depth (cm)
I–II	1 850	4.5	3.2	128
III	4 200	10.1	7.8	104
IV	7 100	17.1	14.6	86
V	8 900	21.4	23.9	61
VI	10 800	26.0	34.7	42
VII	8 700	20.9	48.5	29

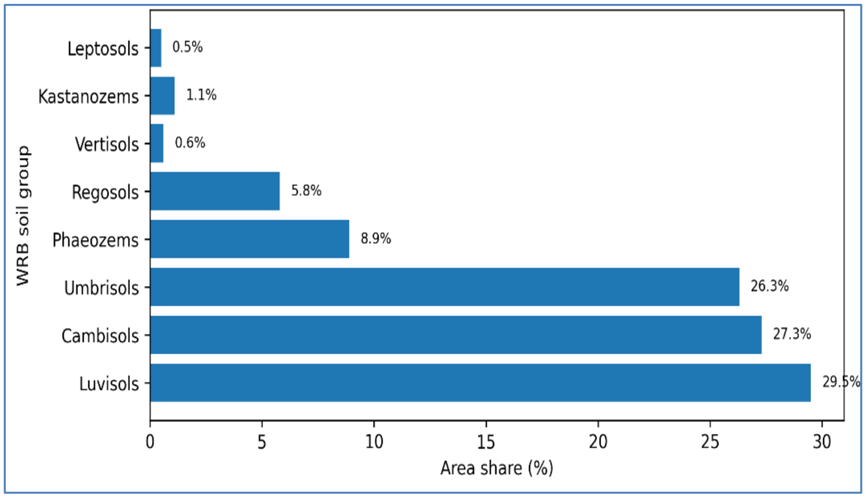

Figure 2: Distribution of WRB soil groups in Kamenica Municipality

class progression indicates a systematic shift from favorable terrain and soil conditions toward increasingly constrained land conditions across the municipality.

High capability land, represented by Classes I-II, occupies only 1,850 ha, corresponding to 4.5% of the total municipal area. These areas are associated with the lowest mean slope gradients recorded in the classification and with the deepest effective soils, averaging 128 cm. Their distribution is limited mainly to valley floors and gently undulating terrain, indicating that only a small proportion of the municipality combines low relief energy with sufficiently deep profiles for more favorable agricultural use.

Class III covers 4,200 ha, or 10.1% of the municipality, and still retains comparatively moderate terrain conditions, with a mean slope of 7.8% and a mean effective soil depth of 104 cm. Although this class remains within the agriculturally usable range, it already marks a departure from the more favorable conditions observed in Classes I-II. Class IV occupies a substantially larger area, 7,100 ha or 17.1%, and represents an intermediate capability category in which mean slope rises to 14.6% while mean effective soil depth declines to 86 cm. Considered together, Classes III and IV account for 27.2% of the municipal area and define a transitional belt between relatively favorable land and land with clearly stronger physical constraints.

A more pronounced change is observed in Class V. This class covers 8,900 ha, or 21.4% of the municipality, and is characterized by a mean slope of 23.9% and a mean effective soil depth of 61 cm. Relative to Class IV, the transition to Class V is associated with both a notable increase in slope and a substantial reduction in soil depth. In real terms, Class V alone exceeds the combined share of high capability land, which underscores the restricted extent of land with more favorable agricultural properties in the municipality.

Very low capability land dominates the overall structure. Classes VI and VII together cover 19,500 ha, corresponding to 46.9% of the municipal area. Class VI alone occupies 10,800 ha, or 26.0%, and is associated with a mean slope of 34.7% and a mean soil depth of 42 cm. Class VII covers a further 8,700 ha, or 20.9%, and represents the most constrained class, with mean slope gradients of 48.5% and mean effective soil depth of only 29 cm. The numerical contrast with Classes I-II is substantial: the highest capability land occupies 4.5% of the municipality, whereas the two lowest classes together occupy almost half of the total area.

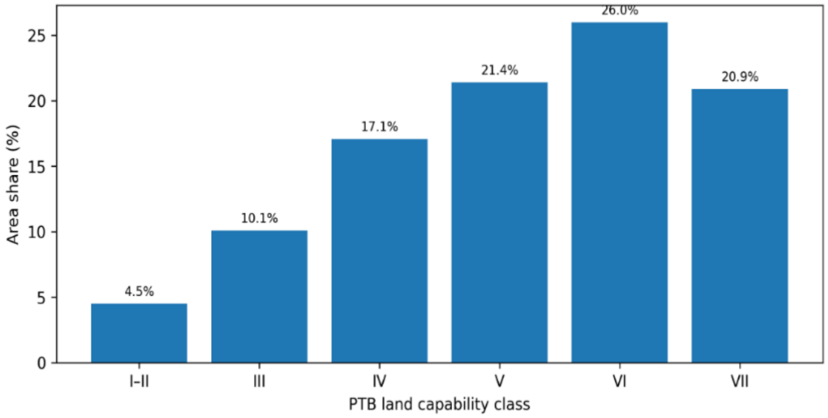

Figure 3: Distribution of agricultural land capability classes (% of area)]

Table 3: Slope class distribution by land capability (% of class area)

Slope class (%)	I–II	III	IV	V	VI	VII
<5	82.4	41.2	18.5	4.1	0.0	0.0
5–10	17.6	38.5	29.7	12.4	3.1	0.0
10–25	0.0	20.3	41.8	35.6	18.7	5.4
25–40	0.0	0.0	10.0	34.2	46.3	21.8
>40	0.0	0.0	0.0	13.7	31.9	72.8

The class distribution shown in Figure 3 is derived directly from the percentage values reported in Table 2 and provides a visual summary of this structure. The figure emphasizes the concentration of land in the lower capability categories, especially Classes V, VI, and VII, and the very limited extent of high capability land. In proportional terms, Classes V-VII together account for 68.3% of the municipality, while Classes I-II account for only 4.5%. This imbalance is one of the central quantitative outcomes of the land capability assessment.

Taken as a whole, Table 2 and Figure 3 show a consistent decline in agricultural land capability across the PTB sequence, expressed numerically through increasing mean slope gradients and decreasing mean effective soil depth. The table does not simply present separate class values; it also reveals an ordered capability structure in which the most favorable classes are spatially limited and the lower capability classes occupy the largest share of the municipal territory.

Terrain controls and Slope–capability relationships

Slope gradient shows a clear and ordered relationship with agricultural land capability across the municipality. The quantitative distribution of PTB capability classes by slope interval is presented in Table 3, which summarizes the percentage share of each class within five slope categories. The table reveals a pronounced redistribution of land capability from higher classes at low slopes to lower classes at steeper terrain positions.

The highest capability land is concentrated almost entirely in the gentlest terrain. Of all land classified as Classes I to II, 82.4% occurs on slopes below 5%, and the remaining 17.6% lies within the 5 to 10% slope interval. No land in this highest capability category occurs on slopes above 10%. This distribution shows that high capability land is confined to the most level parts of the municipality and disappears completely once slope exceeds the lower terrain classes.

Class III follows a similar but slightly wider distribution. A total of 41.2% of Class III occurs on slopes below 5%, while 38.5% lies between 5 and 10%. Together, these two classes account for 79.7% of all Class III land. Only 20.3% of Class III extends into the 10 to 25% interval, and none is present above 25%. This pattern indicates that moderate capability land remains closely associated with gently sloping terrain and becomes uncommon once slope increases beyond the lower gradient classes.

A marked transition is visible in Class IV. Only 18.5% of Class IV occurs on slopes below 5%, and 29.7% falls within the 5 to 10% interval, whereas the largest share, 41.8%, is concentrated in the 10 to 25% slope class. A further 10.0% extends into the 25 to 40% interval. This makes Class IV the dominant category within the intermediate slope range and places it at the center of the overall shift from relatively favorable agricultural land to terrain with increasingly evident physical limitations.

Class V shows a different structure, with its distribution weighted toward steeper terrain. Only 4.1% of this class occurs below 5%, and 12.4% lies between 5 and 10%. The largest shares are recorded in the 10 to 25% and 25 to 40% intervals, which account for 35.6% and 34.2%, respectively, while an additional 13.7% occurs on slopes above 40%. In contrast to Classes I to IV, Class V is therefore centered in the moderate to steep slope ranges rather than in the gently sloping terrain.

The concentration of very low capability land becomes more pronounced in Classes VI and VII. For Class VI, 18.7% occurs in the 10 to 25% interval, 46.3% in the 25 to 40% interval, and 31.9% on slopes above 40%, while only 3.1% lies within 5 to 10% and none occurs below 5%. Class VII is even more sharply concentrated in the steepest terrain. Only 5.4% of this class is found in the 10 to 25% interval, 21.8% in the 25 to 40% class, and 72.8% on slopes above 40%. No Class VII land occurs below 10%, and no Classes I to IV occur above 40%. Taken together, these values show that the steepest slope classes are occupied almost exclusively by the lowest land capability categories.

The 10 to 25% slope interval represents the main transition zone within the municipality. In this class, Class IV becomes the largest category at 41.8%, while Class V already accounts for 35.6% and Class VI rises to 18.7%. The distribution within this interval differs clearly from the two gentlest slope classes, where higher and intermediate capability land predominates. It also differs from the steeper classes above 25%, where low and very low capability land becomes dominant. In practical terms, the 10 to 25% interval marks the point at which the capability structure shifts away from favorable and moderate land toward land with much stronger physical limitation.

This threshold pattern is summarized visually in Figure 4, which was derived directly from the percentage values presented in Table 3. The figure shows a progressive reduction in the share of higher capability classes as slope increases, together with a parallel expansion of Classes V, VI, and VII. The visual pattern is especially clear above the

10 to 25% interval, where the class structure changes from mixed capability to a clear dominance of low and very low capability land.

Overall, Table 3 and Figure 4 show a strong correspondence between increasing slope and declining agricultural land capability. The relationship is not expressed only as a gradual decline across classes, but also as a clear reorganization of the capability structure from higher classes in the gentlest terrain to very low capability classes in the steepest terrain.

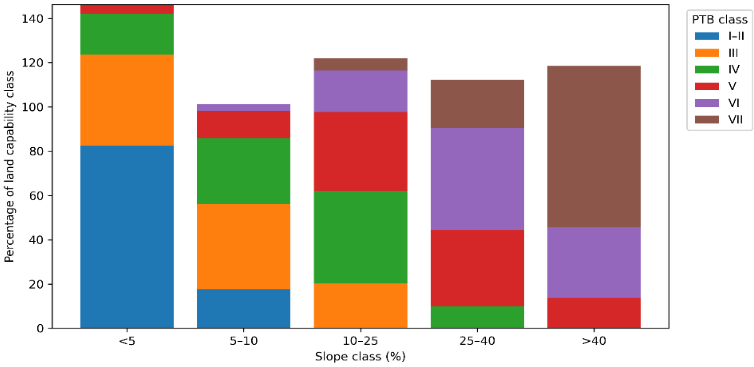

Figure 4: Threshold response of land capability classes to slope gradient

Table 4: Soil depth statistics by land capability class

PTB class	Min (cm)	Mean (cm)	Max (cm)	Std. dev. (cm)
I–II	95	128	165	18.2
III	72	104	148	21.6
IV	55	86	124	19.3
V	38	61	96	17.9
VI	24	42	71	14.5
VII	18	29	54	11.2

Soil depth distribution and reinforcing limitations

Effective soil depth is one of the main physical properties differentiating agricultural land capability across the municipality. Quantitative statistics of effective soil depth by PTB class are presented in Table 4 and show a clear decline in soil depth from the highest to the lowest capability categories. Both the mean values and the minimum and maximum ranges indicate that deeper soil profiles are associated with higher capability classes, whereas low and very low capability land is characterized by progressively shallower effective rooting depth.

Land classified as high capability, represented by Classes I–II, shows the greatest effective soil depth in the municipality. In this class, mean soil depth reaches 128 cm, with a minimum value of 95 cm and a maximum of 165 cm. These values indicate consistently deep soil profiles and distinguish the highest capability land not only by its average condition but also by the absence of very shallow soils within the class. Class III already shows a noticeable reduction, with a mean depth of 104 cm, a minimum of 72 cm, and a maximum of 148 cm. Class IV continues this downward trend, with mean soil depth declining to 86 cm, minimum depth to 55 cm, and maximum depth to 124 cm. Taken together, these classes show that the transition from high to moderate capability is accompanied by a substantial contraction in effective rooting depth.

The decline becomes more pronounced in the lower capability classes. Class V has a mean soil depth of 61 cm, which is less than half the mean value recorded in Classes I–II, and its minimum depth falls to 38 cm. In Classes VI and VII, the profile becomes markedly shallow. Class VI shows a mean depth of 42 cm, with values ranging from 24 cm to 71 cm, while Class VII has the shallowest profiles of all, with a mean depth of only 29 cm, a minimum of 18 cm, and a maximum of 54 cm. These results indicate that shallow soil conditions are not isolated occurrences in the lower classes, but a consistent characteristic of the land occupying those categories.

Variation within the classes also changes systematically. The standard deviation is 18.2 cm in Classes I–II, rises slightly to 21.6 cm in Class III, and then declines through the lower classes to 11.2 cm in Class VII. This pattern suggests that although moderate-capability land still includes a wider spread of soil-depth conditions, the lower capability classes are increasingly dominated by uniformly shallow soils. In other words, as capability declines, not only does average soil depth decrease, but the range of favorable deep-soil conditions also becomes progressively narrower.

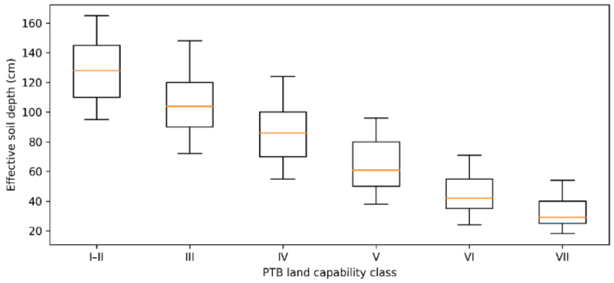

Figure 5: Distribution of effective soil depth by land capability class

The graphical distribution presented in Figure 5 is consistent with the statistical pattern shown in Table 4. The boxplots indicate a clear downward displacement of soil-depth values from high- to low-capability land, with the central tendency shifting steadily toward shallower profiles. The spread of the distributions also becomes narrower in the lowest classes, which corresponds to the smaller standard deviations reported in Table 4 for Classes VI and VII. Figure 5 therefore complements the tabulated statistics by showing that the decline in soil depth is not an isolated effect of mean values alone, but a general feature of the full class distributions.

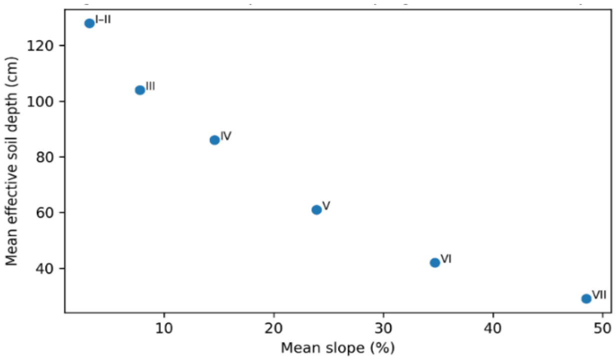

Figure 6: Relationship between mean slope gradient and mean effective soil depth

A second important pattern is the relation between soil depth and slope gradient. Using the mean slope values reported in Table 2 together with the mean soil-depth values in Table 4, Figure 6 shows a strong inverse association between the two variables. Mean effective soil depth declines from 128 cm at a mean slope of 3.2% in Classes I–II to 104 cm at 7.8% in Class III, then to 86 cm at 14.6% in Class IV, 61 cm at 23.9% in Class V, 42 cm at 34.7% in Class VI, and finally 29 cm at 48.5% in Class VII. The decline is therefore continuous across the full capability sequence rather than confined to only one part of the gradient.

This relationship is important because it shows that the reduction in soil depth is closely aligned with the same capability gradient already observed for slope. The higher capability classes combine gentler slopes with deeper soil profiles, whereas the lower classes combine steeper terrain with much shallower profiles. In this sense, Table 4 and Figures 5 and 6 add a second layer of evidence to the capability structure described in Sections 3.2 and 3.3, showing that decreasing land capability is expressed not only in topographic terms but also in progressively reduced effective rooting depth.

Overall, the results presented in Table 4 and Figures 5 and 6 show a systematic reduction in effective soil depth from high- to very low-capability land and a corresponding inverse relationship between soil depth and slope gradient across the PTB classes.

Land suitability differentiation by land use type

Land suitability analysis shows clear differences among the evaluated agricultural land-use types, reflecting their contrasting requirements and tolerance to terrain- and soil-related constraints. Quantitative results are presented in Table 5, which summarizes the proportional distribution of suitability classes for rainfed crops, irrigated crops, perennial crops (orchards), and grazing systems. The table indicates that suitability is not evenly distributed across land uses. Cropping systems are dominated by the lower suitability categories, whereas grazing is concentrated mainly in the moderate and marginal suitability classes.

Rainfed crops show a strongly constrained suitability pattern. Only 5.2% of the municipal area is classified as highly suitable, and 13.5% is moderately suitable. A further 22.7% falls into the marginally suitable class, while the largest share, 58.6%, is classified as not suitable. This means that less than one fifth of the municipality can be considered highly or moderately suitable for rainfed cropping, whereas more than half lies outside acceptable suitability conditions. The rainfed suitability structure is therefore dominated by restriction rather than opportunity.

Irrigated crops present the most restrictive pattern of all evaluated land uses. No land is classified as highly suitable, and only 2.9% is moderately suitable. Even when marginally suitable land is included, the combined share reaches only 15.3%, while 84.7% of the municipality remains not suitable. In proportional terms, irrigated agriculture has by far the largest not-suitable category among all land-use types considered in the study. This distribution distinguishes irrigation clearly from the other land uses and shows that the municipality offers only a very limited area where irrigation could be considered under acceptable physical conditions.

Perennial crops, represented here by orchards, occupy an intermediate position between annual cropping systems and grazing. No land is classified as highly suitable for orchards, but 9.4% is moderately suitable and 31.8% is marginally suitable. At the same time, 58.8% of the area remains not suitable. Compared with irrigated crops, orchards show a broader distribution in the marginal class, indicating that perennial cropping may be feasible in a wider range of locations, although still under evident limitation. Compared with rainfed crops, orchard suitability is slightly stronger in the moderate-plus-marginal range, but the not-suitable share remains almost equally high. The orchard pattern therefore reflects limited but not negligible opportunity, concentrated outside the most strongly constrained parts of the municipality.

Grazing shows a markedly different suitability structure from all cropping systems. No land is classified as highly suitable, but 51.8% of the municipal area is moderately suitable and 34.2% is marginally suitable. Only 14.0% is classified as not suitable. This means that 86.0% of the municipality falls within the moderate or marginal suitability range for grazing, which is substantially higher than the corresponding shares for rainfed crops (41.4%), orchards (41.2%), and irrigated crops (15.3%). Among the four evaluated land-use types, grazing is therefore the only one for which the more usable classes clearly exceed the not-suitable class.

The contrast among land uses is also clear when the distribution is read comparatively across suitability categories. In the highly suitable class, only rainfed crops register any share at all, and even there the value is limited to 5.2%. In the moderately suitable class, grazing is dominant at 51.8%, far exceeding rainfed crops (13.5%), orchards (9.4%), and irrigated crops (2.9%). In the marginally suitable class, orchards and grazing account for the largest shares, at 31.8%

Table 5: Land suitability distribution by land use type (%)

Land use	Highly suitable	Moderately suitable	Marginally suitable	Not suitable
Rainfed crops	5.2	13.5	22.7	58.6
Irrigated crops	0.0	2.9	12.4	84.7
Orchards	0.0	9.4	31.8	58.8
Grazing	0.0	51.8	34.2	14.0

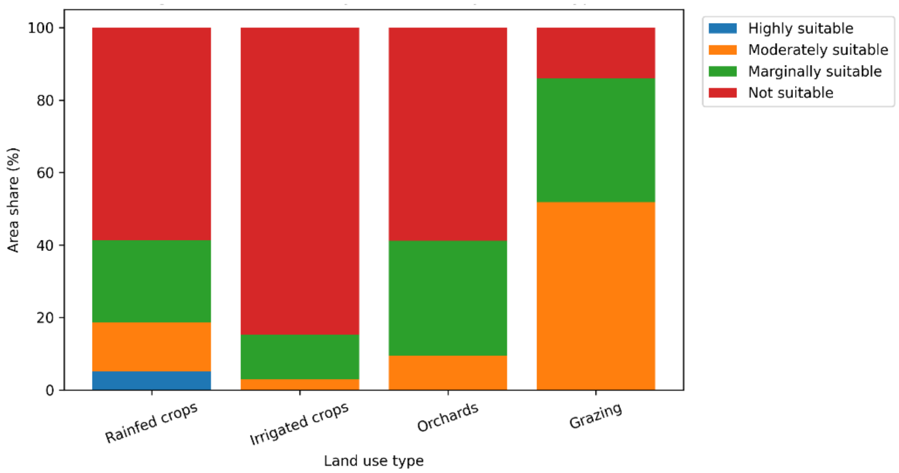

Figure 7: Land suitability distribution by land use type

and 34.2%, respectively, whereas irrigated crops remain lower at 12.4%. In the not suitable class, irrigated crops reach the highest value (84.7%), followed by orchards (58.8%) and rainfed crops (58.6%), while grazing remains much lower at 14.0%. Read together, these comparisons show that the suitability structure differs not only in degree, but also in form, across the four land-use types.

Figure 7 provides a graphical summary of these distributions using the same percentage values reported in Table 5. The figure shows the concentration of rainfed, irrigated, and orchard systems in the not-suitable category, while grazing is concentrated in the moderate and marginal suitability classes. In visual terms, the figure makes clear that the cropping systems share a similar pattern of restricted suitability, whereas grazing follows a distinctly different distribution.

Overall, Table 5 and Figure 7 show that land suitability in the municipality is strongly differentiated by land-use type. Cropping systems are dominated by unsuitable or only marginally suitable land, while grazing is associated with the broadest usable suitability range across the study area.

Multivariate relationships among land evaluation variables

To further examine the interaction among the main variables controlling agricultural potential, a multivariate analysis was conducted using slope gradient, effective soil depth, soil organic carbon content, and the agricultural land capability index. This analysis provides a quantitative summary of the relationships previously observed in the separate evaluations of land capability, slope distribution, soil depth, and land suitability. The correlation matrix presented in Figure 8 shows clear differences in the strength and direction of association among the analyzed variables.

Among all relationships in the matrix, slope gradient shows the strongest association with the land capability index, with a correlation coefficient of $r = -0.88$. This is the largest coefficient in absolute value among the tested variables and indicates that increasing slope is closely associated with declining agricultural land capability. The magnitude of this relationship is consistent with the class structure presented earlier in Table 2 and with the slope-distribution pattern reported in Table 3, where lower capability classes become progressively more dominant as slope increases.

Effective soil depth also shows a strong relationship with land capability, but in the opposite direction. The correlation between effective soil depth and the land capability index is $r = 0.76$, indicating that deeper soils are generally associated with higher capability classes. Although this coefficient is clearly strong, it is lower than the slope–capability relationship, which shows that soil depth is important but not as influential as slope in the overall multivariate structure. This ordering is important because it confirms that the variables do not contribute equally to land capability differentiation across the municipality.

A similarly strong inverse relationship is observed between slope gradient and effective soil depth, with a coefficient of $r = -0.82$. This value indicates that steeper terrain is generally associated with shallower effective soil profiles. In statistical terms, this is the second-strongest relationship in the matrix after slope versus capability. In analytical terms, it links the main terrain variable identified in Sections 3.2 and 3.3 with the soil-depth pattern described in Section 3.4. Figure 9 illustrates this same relationship graphically by showing the decline in mean effective soil depth across the slope-capability sequence.

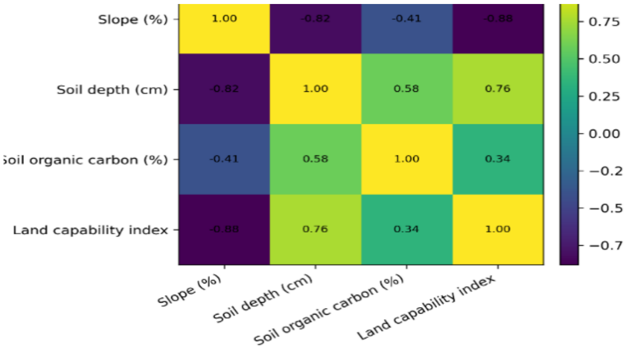

Figure 8: Correlation matrix of key land evaluation variables

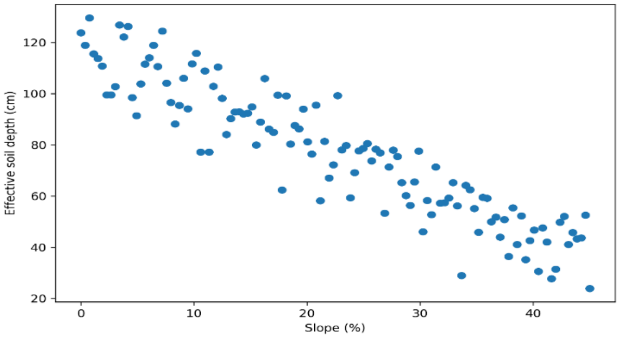

Figure 9: Relationship between slope gradient and effective soil depth

The correspondence between Figures 8 and 9 is especially important here. Figure 8 presents the inverse association statistically, while Figure 9 presents it in plotted form using the class-based mean values. Read together, they show a continuous decline in soil depth from the gentlest terrain with the deepest profiles to the steepest terrain with the shallowest profiles. This pattern is already visible in the earlier results, where mean soil depth declines from 128 cm in Classes I–II to 29 cm in Class VII as mean slope increases from 3.2% to 48.5%. The multivariate analysis therefore does not introduce a separate pattern, but quantitatively consolidates the trends already reported in Tables 2 and 4 and in Figure 6.

Soil organic carbon content shows a weaker role within the multivariate structure. Its correlation with effective soil depth is r = 0.58, indicating a moderate positive association, whereas its correlation with the land capability index is only r = 0.34, which is comparatively weak relative to the slope and soil-depth relationships. These values show that soil organic carbon varies with the broader soil-profile pattern, but it does not differentiate land capability classes as strongly as the physical constraints do. In comparative terms, the land capability index is much more closely aligned with slope and effective soil depth than with soil organic carbon.

When the coefficients are considered together, the multivariate structure becomes more explicit. The strongest relationship is the negative association between slope and land capability (−0.88), followed by the negative relationship between slope and soil depth (−0.82) and the positive association between soil depth and land capability (0.76). The coefficients involving soil organic carbon are notably smaller (0.58 and 0.34). This ranking indicates that the multivariate organization of agricultural potential in the municipality is dominated by terrain and effective profile depth, whereas soil organic carbon plays a secondary role within the analyzed variable set.

The multivariate results also help connect the previous subsections into a single quantitative structure. Section 3.2 showed that lower capability classes are associated with steeper slopes and shallower soils. Section 3.3 showed that land capability declines sharply across increasing slope intervals. Section 3.4 showed that soil depth declines systematically across the same class sequence. The correlation matrix confirms that these patterns are not isolated observations from separate tables, but statistically consistent relationships within the same land-evaluation system.

Overall, Figures 8 and 9 provide quantitative confirmation that the principal gradients in agricultural land capability are closely associated with slope and effective soil depth, while soil organic carbon shows a more limited relationship with the capability structure.

Discussion

Terrain dominance and the hierarchy of controlling factors

The results of this study show that agricultural potential in Kamenica Municipality is governed primarily by terrain-related constraints rather than by soil development alone. Although Luvisols, Cambisols, and Umbrisols together occupy more than 80% of the municipal area, their numerical dominance does not translate into a similarly large share of high-capability land. Instead, the capability structure is strongly weighted toward the lower classes, with 46.9% of the municipality classified as Classes VI-VII and only 4.5% as Classes I-II. This contrast demonstrates that favorable pedogenic development at profile scale does not, by itself, determine agricultural potential at landscape scale. In mountainous terrain, the agricultural value of otherwise favorable soils remains conditional upon topographic setting and the extent to which slope-related constraints allow their productive use.

Among the controlling variables, slope gradient provides the clearest explanation of this pattern. The capability distribution and slope–capability matrix show that higher capability land is concentrated almost entirely in the gentlest terrain, while low and very low capability classes become progressively dominant as slope increases. More than 80% of Classes I-II occur on slopes below 5%, and no high-capability land is present above 10% slope. By contrast, Class VII is concentrated overwhelmingly on slopes above 40%, where it accounts for 72.8% of the class distribution. The transitional zone between 10% and 25% slope is particularly important because this is the interval in which the capability structure shifts from higher and moderate classes toward low and very low classes. This pattern indicates that slope operates not as a minor modifying factor, but as the main organizing variable in the spatial structure of agricultural capability across the municipality.

This threshold-like behavior is important for interpretation because it explains why the municipality contains a relatively limited share of agriculturally favorable land despite the widespread presence of well-developed soils. Once slope moves beyond the lower gradient classes, the cumulative effects of reduced accessibility, greater erosion susceptibility, and more limited cultivation conditions become increasingly difficult to offset. Similar non-linear responses of land degradation and erosion processes to increasing slope have been reported in mountainous environments, where moderate increases in slope often produce disproportionate increases in runoff and soil loss. The present results are consistent with that broader understanding and provide a municipal-scale expression of the same terrain control. Reviewer 1 also specifically asked for updated references in this part of the interpretive framework, so this paragraph is an appropriate place to add one or two newer sources alongside the existing literature.

Effective soil depth strengthens this terrain effect rather than counterbalancing it. Soil-depth statistics across the PTB classes show a systematic decline from 128 cm in Classes I-II to 29 cm in Class VII, while the inverse relationship between mean slope and mean effective soil depth is consistent across the full capability sequence. The multivariate analysis reinforces the same point quantitatively: slope gradient is strongly negatively correlated with the land capability index (r = -0.88), effective soil depth is positively correlated with capability (r = 0.76), and slope and soil depth are themselves strongly inversely related (r = -0.82). Taken together, these values indicate that steep terrain in the municipality is not only difficult because of topographic position itself, but also because it is commonly associated with shallower soil profiles and reduced effective rooting volume. In that sense, slope and soil depth function as compound rather than independent constraints.

The suitability results show how this hierarchy of controlling factors is translated into land-use differentiation. Rainfed crops and irrigated crops are highly restricted, with 58.6% and 84.7% of the municipal area, respectively, classified as not suitable. Orchards occupy an intermediate position, with a broader marginally suitable range but still 58.8% of the area remaining not suitable. Grazing shows a fundamentally different pattern: 51.8% of the municipality is moderately suitable and only 14.0% is not suitable. These contrasts indicate that the central issue is not simply whether land is agriculturally usable in general, but which land use is compatible with the terrain–soil structure that actually exists. Under the conditions observed in Kamenica Municipality, the capability framework and the suitability results converge on the same conclusion: cropping systems are confined to a relatively small proportion of the territory, whereas grazing is compatible with a much larger share of the landscape.

The multivariate structure further clarifies the internal hierarchy among the analyzed variables. Slope has the strongest relationship with capability, effective soil depth has the second strongest, and soil organic carbon shows only a comparatively weak association with the capability index. This does not mean that soil properties are unimportant. Rather, it indicates that in this mountainous environment, physical terrain constraints establish the primary framework within which soil properties influence agricultural performance. Soil organic carbon may still contribute to local soil quality and profile differentiation, but it does not organize the municipal capability pattern as strongly as slope and effective soil depth do. This interpretation is also consistent with Reviewer 2’s assessment that the manuscript effectively demonstrates the dominant influence of terrain factors, particularly slope gradient, on land capability and suitability.

Overall, the discussion confirms that agricultural land evaluation in mountainous regions cannot be based on soil classification alone. In Kamenica Municipality, agricultural potential emerges from the interaction between pedological conditions, terrain morphology, and land-use requirements, with slope gradient providing the dominant structural control and effective soil depth acting as a closely associated secondary constraint. The consistency of this pattern across the soil survey, capability classification, slope analysis, soil-depth statistics, suitability assessment, and multivariate analysis supports the robustness of the integrated soil–terrain framework applied in this study.

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Reinforcing role of soil depth and Implications for land suitability

Effective soil depth acts as a reinforcing constraint on agricultural potential in Kamenica Municipality. The results show a systematic decline in mean soil depth from 128 cm in Classes I–II to 29 cm in Class VII, while mean slope increases from 3.2% to 48.5% across the same capability sequence. This pattern indicates that shallow soils are concentrated in the steeper parts of the municipality, where they intensify existing terrain limitations rather than compensate for them.

The multivariate analysis supports the same interpretation. Effective soil depth is positively related to land capability (r = 0.76), whereas slope gradient is negatively related to both land capability (r = −0.88) and soil depth (r = −0.82). Together, these relationships show that lower-capability land is associated not only with steeper slopes but also with progressively reduced effective rooting depth.

These combined constraints are directly reflected in land suitability. More than half of the municipality is classified as not suitable for rainfed crops (58.6%) and orchards (58.8%), while irrigated crops are even more restricted (84.7% not suitable). Grazing shows a contrasting pattern, with 51.8% of the area classified as moderately suitable and only 14.0% as not suitable. This indicates that shallow soils and steep terrain sharply limit cropping systems, whereas grazing remains comparatively compatible under the prevailing physical conditions.

Similar soil–terrain interactions have been reported in mountainous environments, where slope controls both soil thickness and land-use feasibility (Bockheim *et al*., 2014; Sauer *et al*., 2018; Panagos *et al*., 2025). In this study, soil depth should therefore be interpreted as a secondary but important control that strengthens the effect of terrain on agricultural suitability.

Implications for sustainable land management and Framework transferability

The results of this study have direct implications for sustainable land management in mountainous environments. The dominance of low and very low capability land indicates that policies promoting intensive cropping on steep slopes are unlikely to be environmentally sustainable or economically viable. Instead, land-use planning in Kamenica Municipality should prioritize extensive systems, grazing, agroforestry, and conservation-oriented management in areas where terrain and soil limitations are severe. Such an approach is consistent with broader soil-protection and land-degradation literature, which emphasizes the need to align land use with inherent physical constraints in order to reduce erosion risk and maintain long-term land productivity (Lal, 2015; Panagos *et al*., 2015; Keesstra *et al*., 2016).

The slope thresholds identified in this study also provide a practical basis for land-use zoning. The marked decline in land capability beyond the 10 to 25% slope interval suggests that areas above this range should be treated with greater caution in spatial planning and should be prioritized for soil conservation, erosion control, or ecosystem restoration. Similar threshold-type behavior has been reported in erosion and geomorphological studies, where increasing slope is associated with disproportionate increases in runoff, soil loss, and management difficulty (Moore *et al*., 1993; Montgomery and Dietrich, 1994; Borrelli *et al*., 2017).

A further implication is methodological. A major strength of the present study is the integration of soil survey data, GIS-based terrain analysis, land capability classification, land suitability assessment, and multivariate statistics within a single analytical framework. By combining pedological and geomorphological controls, this approach avoids the limitations of single-factor land evaluation and provides a more realistic basis for agricultural planning in complex terrain. Because it relies on widely used classification systems and commonly available spatial data, the framework is also transferable to other mountainous regions facing similar land-use challenges (De la Rosa *et al*., 2004; Hengl *et al*., 2017).

Conclusions

This study provides an integrated assessment of agricultural land capability and land suitability in Kamenica Municipality, combining soil survey data, GIS-based terrain analysis, PTB land capability classification, FAO-based land suitability evaluation, and multivariate statistical analysis. The results show that agricultural potential in the municipality is controlled primarily by terrain-related constraints, even though the dominant soils are generally well developed. Luvisols, Cambisols, and Umbrisols together account for 83.1% of the municipal area, yet this pedological dominance does not translate into extensive high-capability land at the landscape scale. Land capability analysis demonstrates a clear dominance of lower capability classes. High-capability land, represented by Classes I-II, occupies only 4.5% of the municipality, whereas Classes VI-VII together account for 46.9%. This contrast indicates that soil type alone is insufficient to explain agricultural potential in complex mountainous terrain. Instead, slope gradient acts as the principal limiting factor, with a marked decline in capability beyond the 10-25% slope interval. More than 80% of high-capability land occurs on slopes below 5%, while Class VII is concentrated mainly on slopes above 40%, confirming the strong threshold effect of terrain on agricultural use. Effective soil depth further strengthens this pattern. Mean soil depth declines systematically from 128 cm in Classes I-II to 29 cm in Class VII, while the multivariate analysis shows a strong negative relationship between slope and land capability and a similarly strong inverse relationship between slope and soil depth. These results indicate that steep terrain and shallow soil profiles commonly occur together and form compound limitations that restrict cropping potential across much of the municipality. Soil organic carbon, by contrast, shows a weaker relationship with land capability, which suggests that physical constraints are more important than fertility-related variables in shaping the overall capability structure. The land suitability assessment confirms that agricultural potential is strongly land-use dependent. Rainfed crops, irrigated crops, and orchards are all highly restricted, with

58.6%, 84.7%, and 58.8% of the area, respectively, classified as not suitable. Grazing shows a fundamentally different pattern, with 51.8% of the municipality classified as moderately suitable and only 14.0% as not suitable. This indicates that extensive grass-based systems are far better aligned with the prevailing soil-terrain conditions than intensive cropping systems. From a practical perspective, the findings support land-use planning strategies that restrict intensive agricultural development to the limited areas with favorable slope and soil-depth conditions, while prioritizing grazing, conservation-oriented management, and soil-protection measures in steeper terrain. More broadly, the consistency of the results across soil classification, capability analysis, suitability assessment, and multivariate statistics confirms the robustness of the integrated soil-terrain framework applied in this study**.**

Author contributions

PA: Conceptualization, Methodology, Formal analysis, Investigation, Writing original draft.
YK: Conceptualization, Supervision, Methodology, Writing review & editing.

BA: Methodology, Validation, Writing – review & editing, Scientific consultation.

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Competing interests

No conflict of interest

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