

Optimizing Land Management: A GIS-Based Model for Sustainable Agricultural Machinery Operation in Frakulla Administrative Unit, Albania

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Abstract

In the Frakulla Administrative Unit, Albania, fragmented landholdings and diverse topography constrain efficient agricultural machinery deployment, increasing operational costs and soil degradation risks. This study developed a GIS-based land suitability model to identify optimal zones for sustainable machinery operation using multi-criteria decision analysis (MCDA) and specifically the Analytical Hierarchy Process (AHP). Five biophysical criteria slope, soil texture, soil depth, elevation, and distance to roads were standardized, weighted via AHP, and integrated through raster calculator in QGIS at 30-m resolution, after excluding non-agricultural areas (built-up zones, forests, water bodies) through Boolean constraints. The model classified 21.1% of Frakulla's agricultural land as highly suitable, 35.9% as moderately suitable and 10.6% as marginally suitable for machinery operations, with the remaining 33.4% restricted. By spatially delineating machinery compatible zones, this research advances methodological rigor in combining AHP-weighted criteria with GIS raster-based techniques for mechanization planning in fragmented agricultural landscapes. The resulting suitability map provides actionable intelligence for farmers and planners to allocate machinery strategically, thereby reducing fuel consumption and compaction, preserving soil structure and enhancing long-term productivity and environmental sustainability in the region.

Keywords: Agricultural Mechanization Spatial Modelling, Land Capability Classification, Multi-Criteria Decision Analysis (MCDA), Raster Based Analysis, Soil Conservation

1. Introduction

1.1 Relevance

Efficient and sustainable deployment of agricultural machinery is a pressing priority in the Frakulla Administrative Unit. Highly fragmented landholdings elevate non-productive travel time between fields, while contrasting relief and uneven road access can raise costs and accelerate soil degradation when equipment is used in unsuitable locations. This GIS-AHP model addresses these challenges by optimizing machinery placement. Despite advances in agricultural land assessment methodologies [1], no previous research has applied the GIS-AHP framework to evaluate mechanization suitability in Albania, particularly through the simultaneous integration of topographic (slope, elevation), edaphic (soil texture, soil depth), and

accessibility (road proximity) parameters. This study addresses that research gap by developing a GIS-based land-suitability model that integrates five key factors—slope, soil texture, soil depth, elevation, and distance to roads—weighted with the Analytic Hierarchy Process to indicate where machinery can operate safely, efficiently, and with minimal environmental risk. The GIS-AHP approach is particularly suited to Albania's fragmentation issue because it systematically handles multiple spatial criteria of varying importance and produces transparent, replicable suitability maps that can accommodate both expert judgment and local conditions. The aim is to provide a practical, GIS-based decision tool for farmers, planners, and local

authorities to guide machinery allocation and infrastructure investment. The article is organized into five sections and clearly signposted subsections: Section 1 introduces the motivation and lays out the study objectives, with Section 1.2 providing a focused literature context. Section 2 details the workflow, covering the study area (2.1), the methodology framework (2.2), the criteria and their rationale (2.3 with 2.3.1–2.3.5 for slope, texture, distance to roads, soil depth, and elevation), data sources and preprocessing (2.4), standardization of criteria (2.5), AHP weighting (2.6), and the weighted overlay procedure to generate the final map (2.7). Section 3 presents the results, including thematic maps and summary statistics. Section 4 discusses methodological choices, compares patterns with related studies, and highlights management and policy implications. Section 5 concludes with concise, actionable takeaways for sustainable mechanization in Frakulla.

1.2 Background and Related Work

Agriculture is a cornerstone of Albania's economy, providing employment for nearly half of the population and contributing around 19% to the national GDP. The country possesses about 695,000 hectares of agricultural land, or nearly one quarter of its total territory, yet this land is highly fragmented: the average farm size is only 1.26 ha and divided into multiple parcels [2]. Such fragmentation significantly limits the efficiency of mechanized farming and constrains the adoption of modern technologies.

The Fier District, where the Frakulla Administrative Unit is located, represents one of the most intensively cultivated regions in Albania. It contains approximately 122,000 hectares of farmland and more than one quarter of the national agricultural machinery fleet. Out of a total of 34,030 motorized vehicles registered across Albania, 8,366 are located in Fier [3]. It accounts for a substantial portion of the national equipment, which includes wheeled and chain tractors, mini-tractors, sowing machines, mower, autocombines, and tillers. Despite this concentration of tractors and equipment, current resources are insufficient to meet the sector's growing demands. Inappropriate use of machinery often accelerates soil degradation, reduces water infiltration, and increases operational costs, thereby undermining long-term sustainability [4].

The sustainable operation of agricultural machinery is thus a critical priority for modern land management. Emerging technologies, such as automation systems and precision agriculture tools, aim to enhance efficiency while reducing

environmental impacts [5]. Geospatial methods, including Geographic Information Systems (GIS) and remote sensing, have proven effective in monitoring land use, detecting change, and supporting policy planning across the Western Balkans [6].

Over the past two decades, GIS-based Multi-Criteria Decision Analysis (MCDA), and specifically the Analytical Hierarchy Process (AHP), has become widely used in land suitability assessment. These approaches integrate environmental, technical, and socio-economic factors into spatial models, enabling more accurate and objective decision-making [7]. Applications include crop suitability evaluation, water resource management, and erosion risk analysis. For instance, GIS-MCDA has been used to assess land suitability for achieving SDG 6 targets on water resources [8], to delineate groundwater recharge zones in the Eastern Mediterranean [9], to model soil erosion reduction under different land management practices [10], and to classify river basin networks for improved hydrological planning [11]. In other studies, GIS-MCDA has been employed to evaluate land suitability for agricultural mechanization by assessing terrain and soil physical factors using weighted-overlay analysis integrated with the AHP [12].

Despite this progress, limited research has applied GIS-AHP methods to evaluate agricultural machinery suitability in Albania. Most existing studies focus on crop optimization [13], erosion control [14], or urban land-use planning [15], while the specific challenges of mechanization in fragmented and topographically diverse landscapes remain underexplored. This gap is particularly evident in the Frakulla Administrative Unit, where small farm parcels, varying soil conditions, and infrastructural constraints complicate efficient machinery deployment. The aim of this study was to develop a GIS-based model for assessing land suitability for sustainable agricultural machinery operation in Frakulla. By integrating key criteria such as slope, soil type, depth, elevation, and distance to roads and applying AHP for weighting, the model provides a practical decision-support framework.

2. Materials and Methods

2.1 Study Area

The study was carried out for Frakulla administrative unit, located between latitudes 40° 40' 41"– 40° 35' 12" N and longitudes 19° 28' 49"– 19° 32' 44" E, located in Fieri municipality, in southwest of Albania (Figure 1).

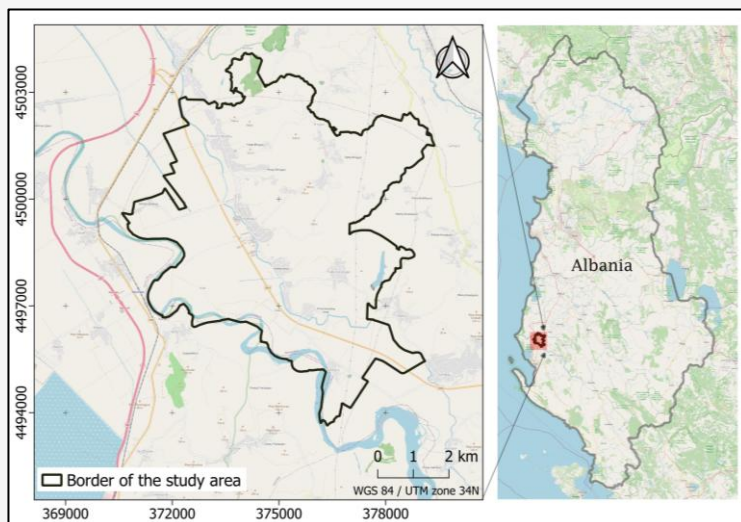


Figure 1: Frakull, Fieri municipality, southwest of Albania

The area of Frakull administrative unit covers approximately 4480 ha. The climate of the area falls within a Mediterranean zone with hot, dry summers and mild, wet winters, featuring an average annual temperature of approximately 18°C and mean rainfall ranging from 750 mm to 1250 mm per year, occurring mainly during winter and autumn [16]. The Frakull Administrative Unit encompasses a flat terrain that stretches towards the northwest, west, south, and southeast, alongside foothills that gradually ascend to the east and northeast before transitioning into steeper slopes. In the flatland, the gradient ranges from 0.5% to 3%, whereas the foothills exhibit inclines from 3.5% to 25%. In other areas of the landscape, the slopes are steeper than 25%. Erosion is a prominent issue affecting substantial parts of the hilly terrain, presenting itself in various forms, including surface erosion, deeper gullies, and even significant landslides. The flatland is predominantly utilized for the cultivation of alfalfa, fruit trees, vegetables, corn, wheat, olive groves, and vineyards [3]. Moreover, extensive tracts of land are either left uncultivated or designated for livestock grazing. Figure 1 shows the borders of the Frakulla Administrative Unit.

In sum, the Frakulla Administrative Unit presents a markedly heterogeneous working landscape: broad, easily accessible alluvial flats used for intensive cropping contrast with dissected foothills and steeper slopes where erosion scars constrain field trafficability and timing. This combination of fragmented holdings, relief-driven variability, and uneven road access directly conditions where machinery can operate safely and efficiently. These biophysical and logistical contrasts justify the study's focus on five determinants slope, elevation,

soil depth, soil texture, and distance to roads –and motivate a weighted, GIS-based evaluation to differentiate operable lowlands from marginal uplands in the analyses that follow.

2.2 Methodology Framework

The methodological workflow is summarized in Figure 2, which illustrates the integration of spatial inputs, standardization, multi-criteria weighting, and overlay analysis for land suitability assessment. Five spatial layers were considered: distance to roads, elevation, slope gradient, soil depth, and soil texture. Land use/land cover was applied separately to generate the constraints map. Constraints were expressed using Boolean masking, a logical operation where cells are assigned binary values of 1 for operable land (permitted conditions) and 0 for restricted land (prohibited conditions such as built-up zones, forests, and water bodies). This discrete metric represents a true or false condition, allowing only two outcomes based on Boolean logic [17]. Each dataset was standardized through a four-class classification to ensure comparability across heterogeneous criteria. The Analytical Hierarchy Process (AHP) was then applied to assign weights reflecting the relative importance of each factor in determining agricultural machinery suitability [18].

The weighted layers were combined through overlay analysis, producing a composite suitability index. Boolean masking was subsequently applied to remove restricted zones such as water bodies, protected areas, or other non-operational lands. The final output is a land suitability map that delineates optimal, moderate, marginal, and unsuitable areas for the sustainable deployment of agricultural machinery in the Frakulla Administrative Unit.

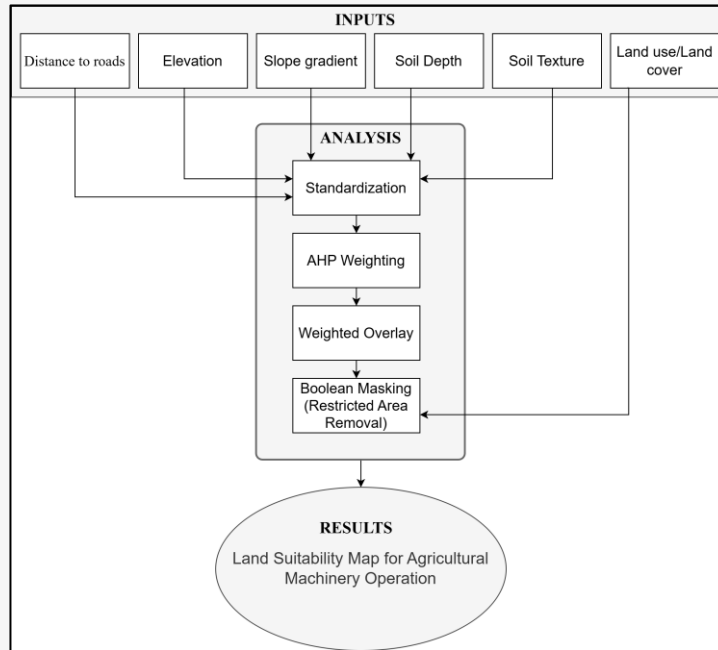


Figure 2: Methodology framework for GIS-based land suitability analysis of agricultural machinery, adapted from AHP-MCDA frameworks

To operationalize this workflow, all preprocessing and analysis were carried out in QGIS 3.40.7. QGIS was chosen over proprietary platforms like ArcGIS due to its open-source nature, which ensures cost-free accessibility and methodological reproducibility without licensing restrictions. The platform's extensive plug-in support and flexible data handling capabilities provided the necessary functionality for conducting the spatial analyses required in this study. Input rasters were harmonized to 30 m resolution and a common UTM 34N (WGS 84) CRS; each criterion was reclassified to a four-level suitability scale (1–4) and its weight normalized so that the weights sum to 1. A constraint mask removed non-operational areas, and a cell-wise final suitability score (FSS) was computed via weighted overlay and then reclassified into the four output classes.

2.3 Criteria Selection and Description

The identification of criteria for land suitability in the Frakulla Administrative Unit was grounded in both biophysical conditions and infrastructural accessibility, as these factors critically determine the efficiency and sustainability of agricultural machinery operation. The process drew upon recent studies in agricultural mechanization, soil science, and GIS-based decision support systems. By combining technical parameters with spatial analysis, a robust framework was established to reflect the realities of farming in this Albanian region. Slope gradient emerged as a decisive factor,

since terrain inclination directly influences machinery stability, traction, and energy requirements. Slopes under 6% were categorized as highly suitable, while those exceeding 20% were deemed unsuitable due to risks of slippage, erosion, and mechanical inefficiency [19] and [20]. Elevation was also included as a key topographical variable. Low-lying areas below 50 meters above sea level were rated highly suitable, whereas suitability progressively declined with altitude, reflecting constraints associated with soil heterogeneity and field accessibility [21].

Soil depth was another crucial criterion. Deep soils exceeding 100 cm provide favorable conditions for root development and allow machinery to operate without exacerbating compaction, while shallow soils below 50 cm limit effective use and accelerate degradation. Closely related is soil texture, where loam was identified as the most suitable due to its balanced aeration and load-bearing capacity. Clay loam and silty clay loam were considered moderately suitable, while heavy clay soils were the least favorable, as they restrict machinery movement and heighten compaction risks [22].

Accessibility was represented through distance to roads [23], acknowledging its role in operational efficiency, fuel consumption, and maintenance logistics. Fields located within 100 meters of a road were highly suitable for mechanization, whereas areas beyond 500 meters were classified as unsuitable, since transport limitations diminish

economic feasibility. Finally, land use/land cover (LULC) provided an overarching spatial filter, distinguishing between arable land, settlements, forests, water bodies and restricted zones.

2.3.1 Slope

Terrain gradient directly affects machinery stability, operational safety, and fuel efficiency during field operations. Steep slopes increase the risk of machinery rollover and reduce traction effectiveness, particularly for heavy equipment such as combines and large tractors. Slopes above roughly 12–20% were treated as operationally limiting in this study, as they reduce tillage quality and increase erosion risk by disrupting consistent implement soil contact and altering draft-force distribution. Additionally, operations on steep terrain require lower working speeds and specialized safety equipment, thereby reducing overall field capacity and increasing operational costs per hectare.

2.3.2 Texture

Soil particle composition directly influences the ground's ability to support machinery weight, resist traffic damage, and maintain structural stability during field operations. Soils with high clay content become problematic for equipment movement when moisture levels are elevated, creating ruts and compaction that can reduce productivity for several consecutive seasons. Sandy soils present opposite challenges by lacking the particle cohesion necessary to distribute machinery loads effectively, causing equipment to sink deeply and operate inefficiently. Loam was taken as the benchmark texture for mechanized operations in this study, since its balanced sand–silt–clay proportions provide adequate bearing strength and traction while maintaining aeration and drainage, limiting rutting and long-term structural damage under repeated traffic [24].

2.3.3 Distance to roads

Access to the road network directly shapes logistics, fuel use, service access, and machine uptime. We operationalized accessibility as the Euclidean distance from the compiled road network and reclassified it into four suitability levels to reflect escalating transport and maintenance constraints based on typical machinery operational ranges and local field conditions: ≤ 100 m (Class 4, highly suitable), 100–300 m (Class 3), 300–500 m (Class 2), and > 500 m (Class 1, not suitable). Shorter distances reduce haulage time and costs and enable faster technical support, while fields beyond ~ 500 m typically face uneconomic travel and delayed service, lowering effective field capacity.

2.3.4 Soil depth

Effective soil depth governs the maximum workable tillage depth, traction behavior, and safe implement selection. In this study, depth was defined as the thickness of the unconstrained working layer above bedrock or other restrictive horizons (e.g., dense clay, cemented or very gravelly layers). Field measurements were interpolated and reclassified into four suitability levels to reflect operational limits: > 100 cm (Class 4, highly suitable), 70–100 cm (Class 3), 50–70 cm (Class 2), and < 50 cm (Class 1, not suitable). Shallow profiles restrict implement penetration, raise the risk of tool strike on hard substrates, concentrate stresses that promote compaction, and typically necessitate lighter machinery, reduced axle loads, and shallower passes. In contrast, deeper soils accommodate conventional tillage systems, broaden implement and tractor choices, and support higher effective field capacity with lower mechanical risk. The class thresholds correspond to common operating depths for primary and secondary tillage with an added safety margin to avoid interaction with restrictive layers [19] and [25].

2.3.5 Elevation

Higher altitudes serve as an indicator of terrain complexity and accessibility constraints that affect agricultural operations. Elevated farming locations typically exhibit substantial soil variability and limited field access due to topographical characteristics, which present operational obstacles for mechanized agriculture. Mountainous and hillside cultivation zones additionally experience logistical complications stemming from irregular terrain features and variable climatic patterns that influence the scheduling of farming activities. Contemporary evaluations of site suitability demonstrate that agriculture in such environments necessitates adaptations to equipment specifications and operational protocols to address performance limitations, particularly concerning engine efficiency under reduced atmospheric pressure and to ensure operational safety throughout cultivation processes [26].

2.4 Data Sources and Preprocessing

The field survey was undertaken using a hand probe to examine the soil profile at a depth of 1.2 m with grid points 300 m apart. This sampling density was selected based on established protocols for agricultural land assessment, ensuring adequate spatial resolution to capture soil variability while maintaining practical feasibility for interpolation methods requiring moderate point density. At each drilling point, a series of soil characteristics were described and recorded [27]. A total of 336 survey

points were collected, and a database containing all the information of the soil for the study area was prepared. At each of the 336 grid points (300 m spacing), the soil profile was augered to ~1.2 m and all discernible horizons were described and sampled. Samples were air-dried, gently disaggregated, and passed through a 2 mm sieve prior to laboratory analysis at the Analytical Laboratory of the Agricultural Transfer Center (Fushë-Krujë, Albania). For mapping purposes, the operational topsoil layer (0–30 cm) was used to derive texture and effective depth surfaces; where present, supplementary samples from 30–60 cm and 60–120 cm were analyzed to document subsoil constraints (e.g., coarse fragments, densic/compact layers). In this study, for mapping the soil properties (texture and soil depth), only the upper layer at 30 cm depth was used. The top 30 cm represents the primary zone of mechanical interaction where tillage operations (plowing, harrowing) and machinery traffic exert the greatest stress, directly influencing draft requirements, fuel consumption and soil compaction risk. For spatial representation of soil parameters, the Inverse Distance Weighting (IDW) interpolation technique was applied using QGIS 3.40.

IDW was selected because it provides robust and computationally efficient predictions for moderately sampled agricultural datasets without requiring assumptions about spatial autocorrelation structure, making it particularly suitable for operational land suitability mapping [28] and [29]. IDW [30] is a deterministic spatial interpolation method that estimates values at unsampled locations based on measured values of surrounding points. The method assigns greater weight to points closer to the prediction location, thereby ensuring that local variations are accurately captured [31]. In this study, the IDW approach was used to produce raster layers of soil depth and soil texture, which were subsequently reclassified into suitability classes for use in the multi-criteria decision analysis framework. The model used in IDW is defined in Equations 1 and 2 [32]:

$$w_i = (d_i^p)^{-1}$$

Equation 1

Where w_i is the weight for the known point i , d_i is the distance between the unknown point x and the known point x_i , and p is the power parameter that controls the rate of weight decrease with distance. The interpolation was performed using a power parameter of 2 [33], which provides a balance between local accuracy and spatial smoothness for soil property mapping, with a variable search radius that included a minimum of 12 nearest neighbours to ensure reliable prediction at each grid cell.

$$a_x = \frac{\sum_{i=1}^n a_i w_i}{\sum_{i=1}^n w_i}$$

Equation 2

Where a_x is the estimated value at the unknown location x , a_i is the known value at point i , w_i is the weight assigned to point i , and n is the total number of known data points.

The land use and land cover map (LULC 2024), which was applied for removing restricted areas, was derived from the Global land use/land cover with Sentinel-2 with a spatial resolution of 10 meters. The dataset was based on satellite imagery from the European Space Agency's Sentinel-2 constellation [34]. For the purposes of this study, the original data were resampled to a 30 m resolution to ensure consistency with other spatial layers.

The elevation raster and slope raster were generated in the QGIS 3.40.7 [30] environment using the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) at 30 m resolution, which has been widely used in GIS-based land evaluation and terrain analysis. Road infrastructure data, required for computing road proximity values, were obtained from OpenStreetMap (OSM) [35], an open-source geospatial dataset. All thematic maps were processed in QGIS 3.40 and harmonized to UTM zone 34N (WGS 1984), consistent with Albanian national mapping standards. This ensured geometric consistency across all spatial datasets used in the analysis [36]. Table 1 shows the data types and sources used.

Table 1: Data type and sources for development of GIS

No.	Data type	Source	Resolution
1	Elevation	USGS	30 × 30 m
2	Slope	Derived from Elevation	30 × 30 m
3	Soil depth	ATTC*	30 × 30 m
4	Soil texture	ATTC*	30 × 30 m
5	Roads	OpenStreetMap	30 × 30 m
6	Land cover	Global land use/land cover with Sentinel-2 https://livingatlas.arcgis.com/landcover/	10 × 10 m (Resampled to 30 m)

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2.5 Standardization of Criteria Layers

In order to execute the weighted overlay, the selected criteria layers were standardized through raster reclassification of their maps. This step ensured that each factor, despite being measured in different units (e.g., slope in percent, depth in centimeters, distance in meters), could be compared within a common evaluation scale [37]. The classification system was based on the guidelines proposed by the FAO framework for land evaluation [38], which is widely applied in land suitability studies. According to this system, the levels most commonly used include: “highly suitable” (S1), “moderately suitable” (S2), “marginally suitable” (S3), “currently unsuitable” (N1), and “permanently unsuitable” (N2). This hierarchical classification allows the differentiation of land according to its capacity to support specific agricultural uses.

However, following the approach adopted in many recent GIS–MCDA-based studies, the last two classes (N1 and N2) were merged into a single category of “not suitable” [39]. This simplification reduces classification complexity and provides a more practical decision-support framework for machinery-related land use evaluation. Consequently, in this study, four standardized suitability levels were applied for agricultural machinery operation as shown in Table 2.

Table 2: Suitability score classification

Score	Abbreviation	Suitability level
4	S1	Highly suitable
3	S2	Moderately suitable
2	S3	Marginally suitable
1	N	Not suitable

This reclassification approach ensured consistency across all input layers and facilitated the weighted overlay process in the GIS environment, allowing for the integration of heterogeneous criteria into a unified suitability model.

2.6 Application of the Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) [18] was employed to determine the relative weights of the

evaluation criteria, ensuring that their total sum equals 1. Pairwise comparison matrices (PCM) (Table 3) were constructed using Saaty’s nine-point ratio scale, where each criterion was compared with every other according to its relative importance. The principal eigenvalue (λ_{max}) of the matrix was used to derive the consistency index (CI), as shown in Equation 3:

$$CI = \frac{\lambda_{max} - 1}{n - 1} \quad \text{Equation 3}$$

Where n represents the number of criteria. The consistency ratio (CR), shown in Equation 4, was used to verify the logical coherence of expert judgments, with $CR < 0.1$ considered acceptable [40]. The random index (RI) is an index that depends on the number of elements being compared. This procedure provided a transparent and reproducible weighting scheme for slope, soil texture, soil depth, elevation, and distance to roads, guaranteeing the robustness of the final suitability model.

$$CR = \frac{CI}{RI} \quad \text{Equation 4}$$

2.7 Development of the Land Suitability Map

The integration of all evaluation criteria was conducted through a weighted overlay analysis in QGIS 3.40.7 [41]. This technique is commonly used in GIS-based multicriteria decision analysis, as it allows several thematic layers with different measurement units to be combined into one composite suitability layer. Each standardized thematic map (STM_i) was weighted according to the importance values (W_i) derived from the Analytic Hierarchy Process (AHP) [18], ensuring that the final evaluation reflected both the physical characteristics of the land and the operational needs of agricultural machinery. The raster calculator in QGIS was applied to implement the overlay model. For each grid cell, the suitability score was computed as the sum of the standardized value of a given factor multiplied by its corresponding weight [42].

Table 3: Pairwise Comparison Matrix for the five criteria

	Sl	St	Dr	Sd	El
Slope (Sl)	1	1	2	2	3
Soil Texture (St)	1	1	1	2	3
Distance to Roads (Dr)	1/2	1	1	2	2
Soil Depth (Sd)	1/2	1/2	1/2	1	2
Elevation (El)	1/3	1/3	1/2	1/2	1

$$CR = 0.02; \lambda_{max} = 5.07$$

This produced the Final Suitability Score (FSS) according to Equation 5:

$$FSS = \sum_{i=1}^n STM_i \times W_i$$

Equation 5

Once the weighted overlay was completed, the output raster was reclassified into four land suitability classes as presented in Table 2. The classification provided a clear framework for identifying zones where machinery operations can be carried out efficiently, areas where adjustments are necessary, and locations that should be avoided due to physical or logistical limitations. The resulting Land Suitability Map for Agricultural Machinery Operation in the Frakulla Administrative Unit represents a practical decision-support tool. It can be used by farmers to optimize machinery deployment, by planners to guide investment in rural infrastructure, and by policymakers to develop strategies that enhance agricultural sustainability in Albania.

3. Results

The integration of all standardized and weighted criteria layers through weighted overlay analysis in QGIS produced a final suitability index, which was reclassified into four land suitability classes. These classes indicate the extent to which land in the Frakulla Administrative Unit can support sustainable agricultural machinery operations. To balance the heterogeneous factors, weights were determined using the AHP.

The results highlighted slope gradient (30%) and soil texture (25%) as the most influential parameters, followed by distance to roads (20%), soil depth (15%), and elevation (10%). The calculated consistency ratio ($CR = 0.02$) confirmed the reliability of the pairwise comparisons. This structured weighting procedure ensures that the final suitability model reflects both the physical environment and the practical requirements for sustainable machinery use. Table 4 presents the suitability classes, score thresholds and the AHP weights assigned to the five parameters. Taken together, these thresholds and weights constitute the standardized scoring backbone for the subsequent AHP-weighted overlay, with slope and soil texture exerting the greatest influence on the final suitability map. The classification scheme, based on the final suitability score (FSS), is presented in Table 5. Highly suitable land represents areas where conditions are nearly ideal for mechanization, allowing maximum efficiency with minimal ecological risks. Moderately suitable zones require some management adjustments but remain largely viable. Marginally suitable land presents significant limitations, where operations may still be possible but at higher costs and risks. Finally, not suitable areas should be excluded from mechanized farming to prevent both economic loss and land degradation [43]. The classification of land suitability for agricultural machinery operation resulted in four distinct categories: highly suitable, moderately suitable, marginally suitable, and not suitable land.

Table 4: Suitability classes, scores, and weights of the criteria considered

Factor	Range of values	Suitability score	AHP Weights (%)
Slope	≈ < 6%	4	30
	6-12%	3	
	12%-20%	2	
	(≈ > 20%)	1	
Elevation	< 50 m	4	10
	50-100 m	3	
	100-200 m	2	
	200-400 m	1	
Soil Depth	> 100 cm	4	15
	70-100 cm	3	
	50-70 cm	2	
	<50 cm	1	
Soil Texture	Loam	4	25
	Clay Loam/Silty Clay loam	3	
	Clay	2	
Distance to Roads	< 100 m	4	20
	100-300 m	3	
	300-500 m	2	
	> 500 m	1	

Table 5: Final suitability classification for agricultural machinery operation

Final suitability score	Classification	Description
> 3.5	Highly suitable land	Optimal terrain, deep loamy soils, close to roads, minimal elevation limits.
2.5 – 3.5	Moderately suitable land	Favorable overall but with moderate limits (slope, soil, or distance to roads).
1.5 – 2.5	Marginally suitable land	Shallow soils, steeper slopes, or longer road distances; partially operable.
< 1.5	Not suitable land	Severe restrictions (steep terrain, clay soils, poor access); unsuitable for mechanization.

The thresholds defined in Table 5 served as the basis for interpreting spatial outputs. Areas with a final suitability score above 3.5 were categorized as highly suitable, while those below 1.5 were identified as not suitable. The intermediate ranges represented moderate and marginal suitability, respectively. This classification framework provided a structured basis for the subsequent mapping and evaluation of each criterion.

Among the evaluated factors, slope emerged as the most influential in determining land suitability. Gentle slopes below 6% were identified as highly suitable due to their minimal constraints for machinery movement, stability, and operational efficiency. Conversely, steep slopes above 20% were classified as not suitable, since they significantly increase the risks of slippage, erosion, and mechanical inefficiency, limiting their capacity to sustain agricultural mechanization. Intermediate slope ranges (6–12% and 12–20%) contributed to moderately and marginally suitable zones, reflecting transitional conditions where machinery can operate but with reduced efficiency and higher maintenance costs [44]. The spatial distribution of slope suitability across the Frakulla Administrative Unit is presented in Figure 3(a).

The slope suitability map clearly illustrates the spatial differentiation of agricultural land according to terrain inclination in the Frakulla Administrative Unit. The central and western flatlands, covering the majority of the study area, fall into the highly suitable class (Class 4), where slopes below 6% allow for stable, efficient, and safe machinery operations. Surrounding these plains, moderately suitable zones (Class 3) form transitional belts along the foothills with slopes between 6% and 12%, where mechanization is feasible but requires more careful management. Areas classified as marginally suitable (Class 2), with slopes between 12% and 20%, are concentrated in the northeastern and eastern margins, where traction limitations and erosion risks reduce field efficiency. The not suitable class (Class 1) dominates the northern and eastern hill slopes, where inclinations above 20% make machinery use

impractical due to high risks of slippage, soil degradation, and mechanical inefficiency.

These spatial patterns confirm that slope gradient is the single most decisive factor shaping land suitability for mechanization in Frakulla. Flat and gently sloping terrains provide optimal opportunities for sustainable farming, while hilly areas remain structurally constrained despite their agricultural potential [45]. The elevation suitability map, presented in Figure 3(b), demonstrates that altitude exerts a clear influence on the distribution of mechanization potential in the Frakulla Administrative Unit. The southern and central lowlands, particularly in areas adjacent to the Vjosa River, fall into the highly suitable class (Class 4), with elevations below 50 meters above sea level. These areas provide optimal conditions for agricultural machinery operation, as accessibility and terrain uniformity reduce both energy requirements and operational risks. A considerable share of the study area is occupied by moderately suitable zones (Class 3), extending across the central and southwestern sectors. With elevations between 50 and 100 meters, these lands remain favourable for mechanization but may face minor constraints, especially under conditions of soil variability or seasonal flooding.

In contrast, marginally suitable areas (Class 2) dominate the northern and northeastern foothills, where elevations of 100–200 meters limit mechanization due to increasing slope complexity and reduced soil uniformity. Finally, the not suitable class (Class 1) is concentrated in the northern and eastern highlands, where elevations surpassing 200 meters impose significant restrictions. Here, rugged terrain, combined with erosion and poor accessibility, renders mechanization impractical. Overall, the results highlight that low-lying flatlands provide the most favourable opportunities, while suitability declines progressively with increasing elevation. This confirms the decisive role of altitude in shaping the spatial configuration of agricultural machinery suitability, complementing the findings from slope analysis.

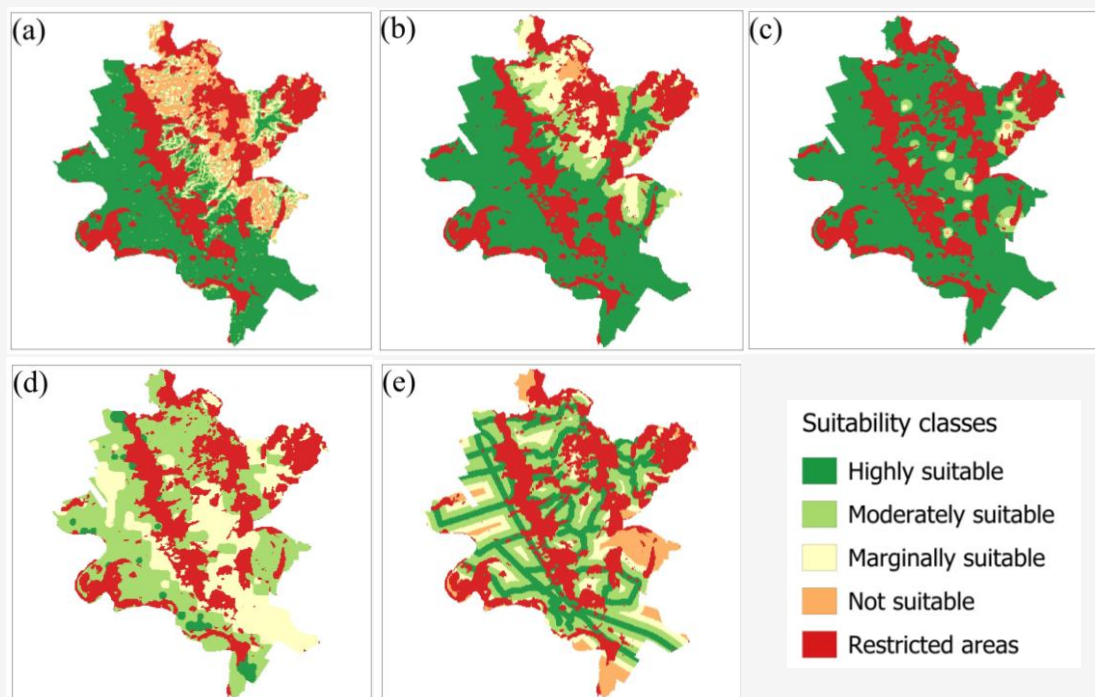


Figure 3: Classified input parameters:
(a) slope (b) elevation (c) soil depth (d) soil texture (e) distance to roads

The soil-depth suitability map, depicted in Figure 3(c), mirrors the IDW-interpolated depth surface (0–30 cm horizon) reclassified by thresholds used in this study (> 100 cm = Class 4; 70–100 cm = Class 3; 50–70 cm = Class 2; < 50 cm = Class 1) [38]. Visually, Class 4 (highly suitable) is the most extensive, occupying much of the study area—especially the central and southern lowlands and many eastern–northeastern valley bottoms and toe-slopes – where recent alluvial deposits provide >100 cm effective depth and allow maximum operational flexibility. Class 3 (moderately suitable) constitutes the second largest share, forming belts and patches around Class 4 cores and on transitional terraces; with 70–100 cm effective depth, these areas offer sufficient working depth for routine tillage and conventional machinery, albeit with slightly higher risk of subsoil interaction under adverse conditions. These locations are best suited for heavy equipment and deeper tillage when required.

Class 2 (marginally suitable) appears as narrow, fragmented bands that fringe the plains and mark transitions to the hills. Here, 50–70 cm depth imposes operational limits (reduced implement penetration, higher risk of compaction), so careful speed/load management is needed. Class 1 (not suitable) is widespread across the northern and eastern hilly terrain, reflecting shallow profiles (< 50 cm) on eroded slopes and lithic contacts. These zones

present a high risk of tool strike and structural degradation under traffic and should be excluded from mechanized operations or restricted to very light, low-pressure equipment with conservation practices. Taken together with the slope and elevation results, the soil-depth map reinforces a clear lowland upland contrast: deeper, more workable profiles in the plains versus shallow, erosion-prone soils on dissected hills where mechanization is impractical or uneconomical. The soil texture suitability map, shown in Figure 3(d), highlights the strong influence of particle composition on the spatial distribution of mechanization potential.

Class 4 (highly suitable), representing loam textures, is limited to small pockets scattered mostly in the southern and southwestern parts of the study area. These locations offer the best balance between aeration, water retention, and bearing capacity, thus providing optimal conditions for heavy machinery use without inducing compaction or rutting. Class 3 (moderately suitable), corresponds to clay loam and silty clay loam textures. These soils provide adequate support for mechanized operations but require careful traffic management under wet conditions to minimize compaction risks. Class 2 (marginally suitable), where heavier clay fractions constrain machinery movement and increase susceptibility to traffic-induced degradation. While mechanization is

possible, operations in these zones are energy-intensive and prone to reduced efficiency during moist seasons. Restricted areas (red) appear most extensively in the northeastern hills and as fragmented patches across the foothill zones. These areas, characterized by high clay content and shallow rooting conditions, restrict efficient equipment deployment and pose long-term risks of structural damage under repeated machinery use. The distribution of classes confirms that soil texture interacts closely with slope and depth to shape mechanization feasibility. The central lowlands, where loam and clay loam prevail, remain the most promising areas for sustainable machinery deployment, while the peripheral hills and clay-rich zones represent critical constraints. Building on the edaphic constraints highlighted by the soil texture map, accessibility further structures mechanization potential. Figure 3(e) shows a banded pattern that closely follows the road network: a narrow inner buffer of Class 4 (≤ 100 m) runs directly along the primary corridors, surrounded by a Class 3 belt (100–300 m), then a Class 2 belt (300–500 m). Beyond these buffers, extensive tracts – especially across the northern and eastern uplands and in more fragmented foothill zones – fall into Class 1 (> 500 m, not suitable) due to poor access. The densest swaths of high and moderate suitability trace the central and southern grid of roads, where field entrances and short haul distances reduce fuel use, travel time, and maintenance logistics. In contrast, peripheral hills display long stretches of Class 1, indicating that even where terrain or soils are acceptable, distance from roads becomes the binding constraint for timely field operations and service response.

Taken together with slope and elevation, the distance-to-roads map explains why the central lowlands accumulate the highest final suitability: favorable terrain and soils are reinforced by proximity to transport infrastructure. Conversely, on the outer hills, limited access compounds topographic limits, pulling final scores down despite local pockets of better soils. These results point to clear planning levers – upgrading field access tracks and improving junctions along the existing corridors could convert large Class 2–3 belts into consistently operable areas. The integration of all standardized criteria through the weighted overlay yields the final suitability map presented in Figure 4. This map synthesizes slope, elevation, soil depth, soil texture, and distance to roads, while excluding restricted areas such as settlements, forests, and water bodies. The result provides a spatially explicit assessment of where machinery operations can be carried out efficiently and sustainably. The map reveals a pronounced spatial polarization.

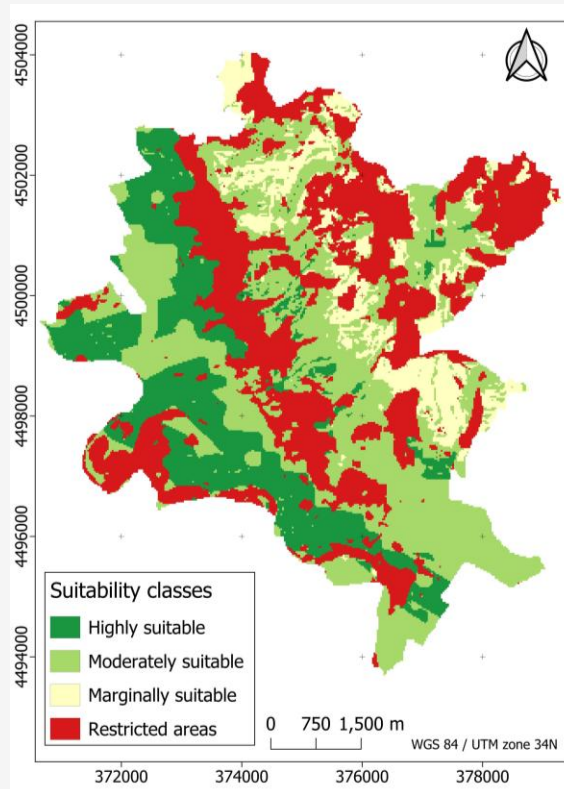


Figure 4: Land suitability for sustainable agricultural machinery operation

Large expanses of the southern and southwestern plains, together with parts of the central lowlands, fall into the highly suitable class (Class 4). These zones combine flat terrain, deep loamy soils, and excellent proximity to road infrastructure, making them optimal for intensive mechanization. Surrounding these, wide belts of moderately suitable land (Class 3) stretch across the transitional zones of the foothills, where one or more factors – often slope or soil depth – begin to constrain operability but still allow for efficient machinery use with minor adjustments. Areas of marginal suitability (Class 2) are concentrated along the northern and eastern uplands, where steeper gradients and shallow soils reduce operational flexibility. In these areas, mechanization is possible but at higher costs and with increased risk of soil degradation. Overall, the map confirms that topography and accessibility jointly determine the spatial distribution of mechanization potential in the Frakulla Administrative Unit. By highlighting the clear divide between the highly suitable lowlands and the restrictive uplands, the final suitability map offers a robust decision-support tool for guiding agricultural investment, machinery allocation, and sustainable land management strategies in the region.

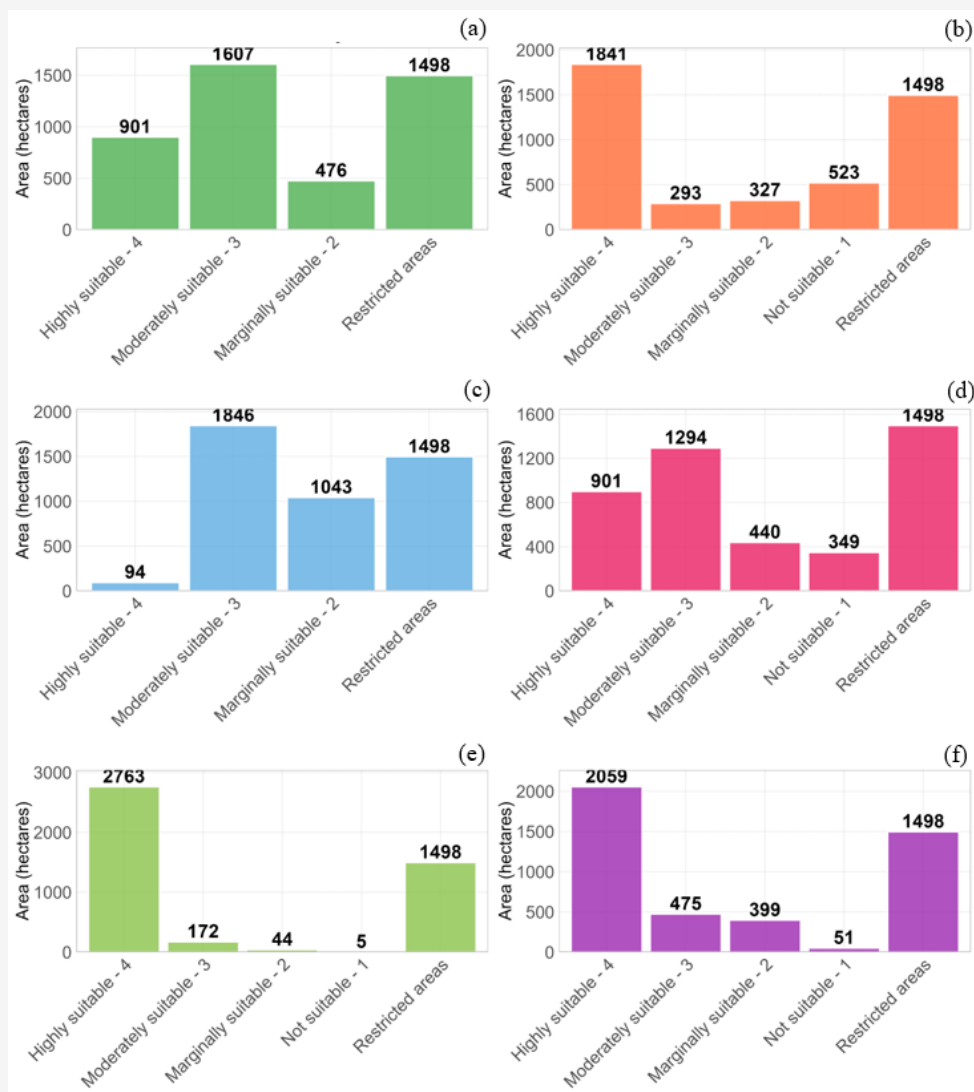


Figure 5: Quantitative synthesis of land suitability for agricultural machinery: (a) overall, (b) slope, (c) texture, (d) distance to road (e) soil depth, and (f) elevation

Figure 5 summarizes the areal distribution (ha) of suitability classes for each criterion and for the final weighted map. Expressed as a share of the total administrative area (4,482 ha), the final suitability distribution is 21.1% highly suitable, 35.9% moderately suitable, 10.6% marginally suitable, and 33.4% restricted. For operational planning, it is also useful to report shares relative to the operable land only – i.e., excluding restricted areas; on this base (2,984 ha) the classes comprise 30.2% highly suitable (901 ha), 53.9% moderately suitable (1,607 ha), and 15.9% marginally suitable (476 ha). Figure 5 reports the corresponding areas in hectares; minor differences between percentages and bar totals reflect rounding and raster-mask alignment and do not affect interpretation. Individually, slope is largely favorable: 1,841 ha (61.7%) fall in the highly suitable

class (<6%), while 523 ha (17.5%) are not suitable (>20%) and cluster on the northern eastern hills. Elevation shows a similar tendency, with 2,059 ha (69.0%) below 50 m a.s.l. and only 51 ha (1.7%) in the highest, restrictive band (>200 m). Soil depth is the least limiting factor: 2,763 ha (92.6%) exceed 100 cm and only 5 ha (0.2%) are <50 cm, confirming that the depth constraint is spatially minor relative to other drivers. By contrast, soil texture emerges as the principal biophysical bottleneck. Only 94 ha (3.2%) are classified as highly suitable (loam), whereas 1,846 ha (61.9%) are moderately suitable (clay loam/silty clay loam) and 1,043 ha (35.0%) are marginal (clay); the truly not-suitable fraction is negligible (≈ 1 ha; 0.03%). This distribution explains why many areas with favorable slope, elevation, and depth are ultimately downgraded in the final overlay:

texture controls trafficability under variable moisture and governs compaction risk. Infrastructure reinforces these patterns. Distance to roads places 901 ha (30.2%) within 100 m of a road (highly suitable) and 1,294 ha (43.4%) within 100–300 m (moderately suitable), but still leaves 440 ha (14.7%) at 300–500 m and 349 ha (11.7%) beyond 500 m, where haulage time, fuel costs, and service delays depress operational efficiency. As a result, otherwise favorable tracts at the edges of the network are pulled into lower classes in the final map. Taken together, the graphs clarify the mechanics behind the final suitability distribution in Figure 5. The dominance of the moderately suitable class (1,607 ha) is consistent with strong positive contributions from slope, elevation, and – especially – soil depth, counterbalanced by the more conservative signal from soil texture and, to a lesser extent, road proximity. The highly suitable area (901 ha) concentrates where loam or lighter clay-loam patches coincide with <6% slopes and lie within 100 m of roads, predominantly across the central–southern plains. The marginally suitable area (476 ha) aligns with clay-rich pockets, transitional slopes (12–20%), and locations >300 m from roads, mostly along the northern and eastern periphery. This quantitative evidence corroborates the cartographic interpretation from Figures 3(a), 3(b), 3(c), 3(d), 3(e) and 4, and pinpoints two actionable levers for improving mechanization potential: targeted soil-traffic management on clayey soils and selective upgrades to field access in peripheral zones.

Overall, the spatial pattern is internally consistent: high final suitability clusters across the central–southern lowlands where gentle slopes, deeper profiles, loam to clay-loam textures, and short road distances co-occur, whereas suitability declines toward the northern and eastern uplands as gradients steepen, clay content rises, and access deteriorates. Soil depth is the least limiting factor in this landscape, while slope and texture form the primary biophysical controls; proximity to roads then amplifies or suppresses operational potential at the parcel scale. This hierarchy of effects aligns with the Analytical Hierarchy Process weighting and explains the dominance of the moderate class in the final overlay.

These results should be interpreted with appropriate caution. Resampling and harmonization of inputs (e.g., Sentinel-2 LULC downscaled to 30 m; SRTM DEM at 30 m) inevitably smooth fine-scale variability in micro-relief and farm tracks. IDW interpolation captures local gradients around soil sampling points but can introduce edge effects near class boundaries. Although the pairwise judgments exhibited strong agreement (CR = 0.02), small

perturbations in AHP weights can shift class breaks in transitional zones. Targeted field checks on cells near thresholds, and periodic updates of LULC and road data, will help keep the map decision-ready.

From a management perspective the map indicates clear levers to raise operability. In high-suitability tracts, concentrating equipment and adopting controlled-traffic practices can sustain efficiency while protecting soil structure. In moderately suitable belts, relatively light interventions – upgrading field access along existing corridors, scheduling operations in drier windows, and using low-pressure tires – can tip parcels into the next class. Marginal areas with clay-rich textures benefit from minimizing passes, shallow or strip tillage, and surface residue management; where distance to roads is the binding constraint, selective access improvements can unlock contiguous zones for safe mechanization. Not-suitable hillsides should be excluded from conventional traffic or shifted to low-impact uses and conservation-oriented practices.

Finally, the maps highlight “transition potential” that can guide scenario testing. Parcels on slopes below ~12% and within 100–300 m of roads are prime candidates for class upgrades via modest access and traffic-management measures, while clay pockets in the lowlands can be improved through moisture-aware scheduling and load reduction. These insights set up the Discussion to compare this pattern with related studies and to outline policy and investment priorities for sustainable mechanization in the Frakulla Administrative Unit.

4. Discussion

The spatial patterning observed in Frakulla – highly suitable lowlands tapering to marginal and not-suitable belts along the northern eastern uplands – aligns with the core expectation of AHP–GIS suitability studies, where terrain and access variables dominate mechanization feasibility. Similar GIS–MCDA frameworks have consistently identified slope and road proximity as primary determinants of operability, with soil properties modulating local variability. This is consistent with the applied weight structure and mapped outcomes. In particular, the tractor-suitability work from Calabarzon [45] demonstrated that gentle gradients and short haul distances are the strongest positive drivers of deployment efficiency, while increasing distance from paved corridors rapidly erodes field capacity – an effect also documented in Frakulla’s peripheral hills.

Edaphic constraints in the model are driven chiefly by texture, not depth – again mirroring recent agronomic evidence. Loam pockets in the central southern plains form the nucleus of Class 4 areas,

whereas clay-rich matrices suppress final scores despite favourable topography [46]. Contemporary soil physics highlights why: high clay content increases susceptibility to traffic-induced compaction, rutting, and persistent structural degradation, particularly under moist conditions; conversely, balanced textures distribute wheel loads more effectively and recover faster between passes [47]. These mechanisms explain the systematic downgrading of otherwise flat tracts on heavy soils in the overlay and point to concrete mitigation levers such as optimized tire technologies, pressure management, and traffic discipline that can materially improve operability without land conversion [48] and [49].

The use of recent Sentinel-2 LULC, increases confidence that constrained classes (settlements, forests, water bodies) were masked with current boundaries, thereby reducing commission errors commonly observed in legacy maps [50] and [51]. Comparable GIS-based susceptibility analyses, such as those applied to non-grain cultivated land in China, further demonstrate the robustness of machine-learning integration in land evaluation [52]. Likewise, GIS-supported monitoring of land use change in Southeast Asia confirms the applicability of such spatial frameworks for supporting sustainable development planning beyond the agricultural context [53] and [54].

The Frakulla results carry direct planning implications that echo international experience. Concentrating heavier machinery and intensive operations within the central–southern plains is consistent with sustainability and energy-efficiency recommendations, while clay-rich belts and road-distant fields should adopt lighter equipment, lower tire pressures, and controlled-traffic or reduced-tillage practices to curb compaction and fuel use [55] and [56]. From a policy angle, modest investments in access – upgrading farm tracks and junctions along existing corridors – can shift wide Class 2–3 belts into consistently operable zones, a finding aligned with AHP–GIS studies that treat accessibility as a high-leverage, rapidly improvable criterion [57] and [58]. Beyond the agricultural domain, the workflow demonstrates how raster-based MCDA can support spatial planning in diverse geomorphological settings, offering a transferable template for infrastructure placement, environmental zoning, and climate adaptation strategies where multiple criteria must be harmonized over large territories. Finally, the broader literature shows how suitability platforms similar to this study are being extended to adjacent decisions. Remote sensing–based approaches demonstrate how land-use and land-cover change detection can inform long-term spatial

planning and agricultural allocation [59] and [60]. At the same time, GIS-based optimization of infrastructure illustrates how similar frameworks can be adapted to improve service delivery and facility siting, such as waste collection systems in urban environments [61][62] and [63].

In sum, the AHP–GIS model reproduces established mechanization logic – terrain and access first, soils as the operational governor – while translating it into actionable maps for Frakulla. The coherence with prior evidence across regions and applications supports the robustness of the findings, and the identified upgrades – soil-traffic management on clayey tracts and selective access improvements – offer immediate, cost-effective pathways to raise mechanization performance without compromising long-term soil function.

5. Conclusions

This study evaluated land suitability for sustainable agricultural machinery operation in the Frakulla Administrative Unit by coupling AHP with RS–GIS and using five criteria (slope, soil texture, soil depth, elevation, and distance to roads). Expert-based weighting highlighted slope and soil texture as the most influential factors, while the soil-depth submodel exhibited the largest share of “highly suitable” areas and the texture submodel was the most restrictive. The final suitability map classifies 21.1% (9.01 km²) as highly suitable, 35.9% (16.07 km²) as moderately suitable, and 10.6% (4.76 km²) as marginally suitable; 33.4% (14.98 km²) of the territory is restricted. This baseline enables Fieri Municipality to strategically allocate its limited machinery resources by directing intensive mechanized operations to the 9.01 km² of highly suitable land while prioritizing infrastructure investments in moderately suitable zones to enhance mechanization potential. The suitability framework offers a practical policy tool for aligning agricultural development strategies with terrain and soil capabilities, ensuring efficient resource allocation and sustainable land management.

Nevertheless, several limitations of the current model should be noted. First, the use of static road-distance buffers may inflate apparent suitability: when road rights-of-way are discontinuous or field entrances are scarce, actual machinery access may be limited. Targeted ground checks of model-identified access points are recommended to validate these hotspots. Second, the model’s static layers do not account for seasonal moisture variations, so trafficability during unusually wet or dry periods could be misrepresented. Incorporating dynamic wetness proxies such as Sentinel-1 SAR-derived moisture indices or conducting seasonal suitability

analyses could more effectively capture these temporal variations [64][65] and [66]. Third, the use of IDW interpolation, which does not account for spatial autocorrelation, anisotropy, or prediction uncertainty may produce localized artifacts around sampling points. Future studies should consider geostatistical methods such as Kriging or machine learning-based approaches [67] that incorporate spatial structure and auxiliary covariates to improve interpolation accuracy and provide uncertainty estimates. We also acknowledge that not all potentially relevant factors were included, variables such as land cover dynamics, erosion risk, or socio-economic constraints could further refine the analysis. Finally, AHP inherently relies on expert judgment and pairwise criteria comparisons, which brings subjectivity and the need for consistency checks. Even with an acceptable consistency ratio, biases may persist. To address this, future studies could explore complementary or hybrid multi-criteria approaches (fuzzy AHP, Analytic Network Process, TOPSIS, or the Best–Worst Method) to triangulate weights and enhance robustness [68] and [69].

Despite these limitations, the integrated GIS–MCDA framework presented here remains a useful starting point. Beyond its immediate application in Frakulla, the approach is transferable to other geographic contexts and can be adapted for broader research applications, including multi-purpose suitability assessments or alternative machinery systems by recalibrating criteria weights and incorporating region-specific data.

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