Soil Degradation and Desertification Risk in the Rif Mountains (Morocco): A MEDALUS-Based Spatial Assessment

Dégradation des sols et risque de désertification dans les montagnes du Rif (Maroc) : une modélisation spatiale basée sur le modèle MEDALUS

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Abstract

This study assesses desertification risk in the Rif Mountains of northern Morocco using eight soil quality indicators within the framework of the Mediterranean Desertification and Land Use Model. The study area covers approximately 27,989 km^2. Landsat satellite imagery and spatial analysis using QGIS 3.12 were employed to process environmental data and generate soil quality indices and thematic maps. The results classify the study area into three categories based on soil resistance and sensitivity to degradation. Areas with high soil quality represent about 36% of the region and are mainly located in forested zones, showing low susceptibility to desertification. Areas with moderate soil quality account for approximately 35%, indicating moderate resistance and higher vulnerability to degradation. The remaining 29% corresponds to low soil quality areas, largely concentrated in the southern part of the region, which are highly sensitive to degradation processes that may lead to desertification. These findings provide valuable insights for land management and desertification mitigation strategies in northern Morocco.

Keywords: MEDALUS. Soil Quality Index. Rif Mountains. Desertification. GIS. Morocco.

Résumé

L'étude évalue le risque de désertification dans les montagnes du Rif, au nord du Maroc, en utilisant huit indicateurs de qualité des sols dans le cadre du Mediterranean Desertification and Land Use Model. La zone d'étude couvre environ 27,989 km^2. Des images satellitaires Landsat et une analyse spatiale à l'aide du QGIS 3.12 ont été utilisées pour traiter les données environnementales et produire des indices de qualité des sols ainsi que des cartes

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thématiques. Les résultats montrent que la zone d'étude est divisée en trois catégories selon la résistance des sols et leur sensibilité à la dégradation. Les zones à haute qualité des sols représentent environ 36% de la région et sont principalement situées dans les zones forestières, présentant une faible susceptibilité à la désertification. Les zones à qualité moyenne des sols représentent environ 35%, indiquant une résistance modérée et une vulnérabilité plus élevée à la dégradation. Les 29% restants correspondent à des zones à faible qualité des sols, largement concentrées dans la partie sud de la région, qui sont fortement sensibles aux processus de dégradation pouvant conduire à la désertification. Ces résultats apportent des éléments utiles pour la gestion des terres et les stratégies de lutte contre la désertification dans le nord du Maroc.

Mots-clés : MEDALUS. Indice de qualité des sols. Montagnes du Rif. Désertification. SIG. Maroc.

1. Introduction

Assessing soil degradation in environmentally sensitive areas prone to desertification in the Mediterranean area requires an accepted definition of desertification, given the evolution of the concept of 'desertification' in relation to 'land degradation' (Salvati et al., 2015). After being associated exclusively with arid and semi-arid regions, it became linked to land degradation in semi-humid areas and in the Mediterranean region (Sivakumar, 2007). Since then, the concept of desertification, according to the United Nations Convention to Combat desertification, has linked desertification to the peak of land degradation, which leads to a continued decline in biological productivity in arid, semi-arid and semi-humid areas. It is also linked to climate change as a driver of desertification (Bauer, 2016). These are human factors through population growth and population density for all systems. Therefore, desertification is linked to the sensitivity of ecosystems and the pressure that humans impose on land resources (Baartman et al., 2007). The development of desertification is often accompanied by aggravating soil erosion (Lal, 2001).

The Rif Mountains in northern Morocco are experiencing accelerating environmental degradation, particularly soil degradation, due to compounded natural vulnerability and increasing human pressure (Laaribya & Alaoui, 2025; Moore et al., 1998). This region is characterized by steep slopes, susceptible lithology, and a Mediterranean climatic condition, exposing it to higher risks of land degradation and natural hazards. However, the most pressing issue is large-scale soil degradation caused by unsustainable land use trends encouraged by illegal forest clearance and other practices such as the over exploitation of steep slopes through cultivation or overgrazing due to the limited agricultural areas resulting from the predominantly steep topography (El Motaki et al., 2019). These activities accelerate soil erosion, reduce biodiversity, and lead to instability of already vulnerable ecosystems (Hatfield et al., 2020).

This study aims (A) to identify land degradation patterns and analyze the principal factors affecting land sensitivity to degradation in the central Rif mountains and its southern margins of Morocco through the applying of spatial analysis techniques. It (B) develops a comprehensive methodology for mapping sensitivity to land degradation, which is typically related to humid, semi-humid or dry subhumid areas, and desertification, which is typically related to semi-arid and arid land, is a broad concept that depends on place-specific socio-ecological conditions, interactions, and adaptation strategies (Kosmas et al., 2016). The Study (c) also provides an opportunity to identify areas most vulnerable to or threatened by degradation leading to desertification. To (D) predict future soil degradation trends under climate change and human pressures for guiding protection efforts in order to enhance development and planning strategies, ensure the sustainability of natural resources and also strengthen the socio-economic situation of the concerned population in the defined study area, as well providing scientific foundation as a global reference for the quantitative and qualitative assessment of land degradation sensitivity and its causes in the study area.

To determine and map the major processes of soil degradation leading to desertification in central Rif, especially the Pre-Rif, Morocco, this study based on applying the method MEDALUS (Mediterranean Desertification and Land Use) method for evaluating and classifying the soil degradation through different parameters used in a sub-humid and semi-arid environment. Factors are overlaid in a geospatial environment to give a spatial variation of soil degradation. Processes based on global datasets featuring texture, parent material types, drainage, slope, and Rock fragment.

Based on the Soil Quality Index (SQI) indicates that around 29% of the study area is highly susceptible to desertification, indicating severe environmental vulnerability. The remaining 71% ranges from medium to low sensitivity levels, which typically occur in less sloping or relatively vegetated zones. Spatial sensitivity distribution is strongly coincidence with zones under intense human pressure, particularly deforestation and informal agricultural development.

These findings underscore the urgent need for sustainable land management strategies and the redesign of territorial governance in forest areas. The study underlines how ecological vulnerability, when coupled with socio-economic constraints and illicit land uses, drives a hazardous and territorial conflict trajectory in this ecologically rich but fragile mountain territory.

2. Method and Materials

2.1. Study Area

The study area extends along the southern margins of the central Rif mountains. The geomorphological structure is characterized by the predominance of high mountainous areas in the north, exceeding 2,400 m at the summit of Taghdzine, while altitudes do not exceed 600 m in the south, where fragile clayey rocks predominate (Figure 1). The spatial distribution of average rainfall in the study area is characterized by a difference between the north and the south depending on factors influencing humidity, including altitude and exposure, with average rainfall exceeding 1,600 mm in the north and about 500 mm in the south of the study area. Temperatures also reach exceptional values, sometimes exceeding 40 °C during the summer months of July and August because of the Easterly winds. Conversely, temperatures decrease to -1 °C, especially in the high areas in the far north of the study area. The central-southern Rif mountains area is exposed to two types of hot and humid air masses, including western winds associated with the Atlantic Ocean and eastern winds that are cold and dry during the winter, hot and dry during the summer, which come from the eastern continental regions and desert areas.

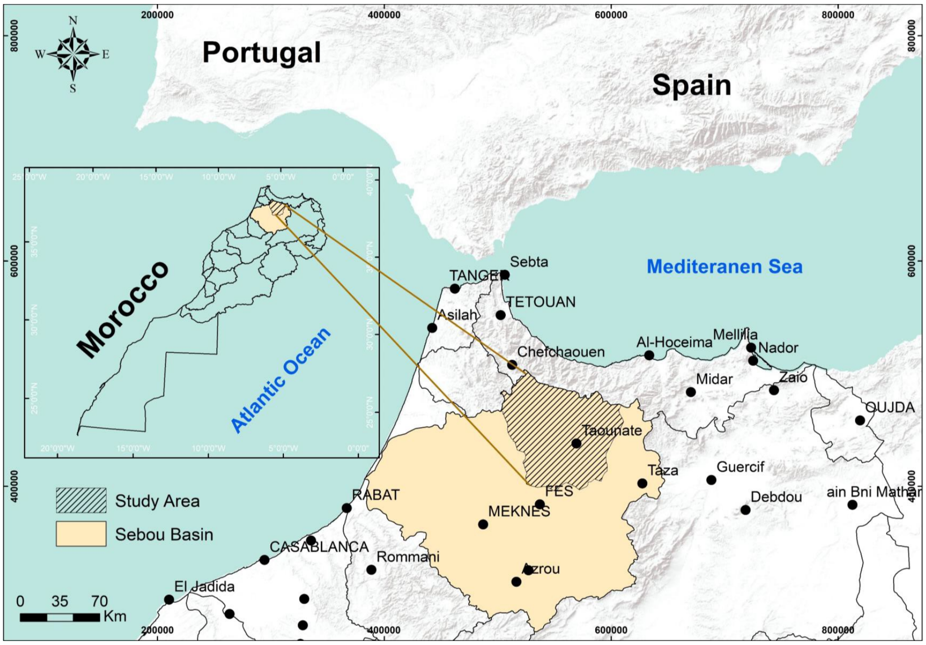

Figure 1. Placement of the study area.

2.2. Data used and processing

To generate the mapping of environmentally sensitive areas susceptible to soil degradation in study area, study is based on the MEDALUS model and the assessment of the most important factors affecting Soil degradation leads to desertification. Accordingly, the study area was defined as a mountainous area. Each factor was considered as an individual study unit, and the assessment of desertification was made in all of them. Each of the six Soil Quality Indices including (texture, parent material, rock fragment, depth, slope, and drainage), were classified and weighted based on the MEDALUS model and their contribution to soil sensitivity to degradation (Imam et al., 2025). The final SQI is computed using the geometric mean of these indicators (Figure 2).

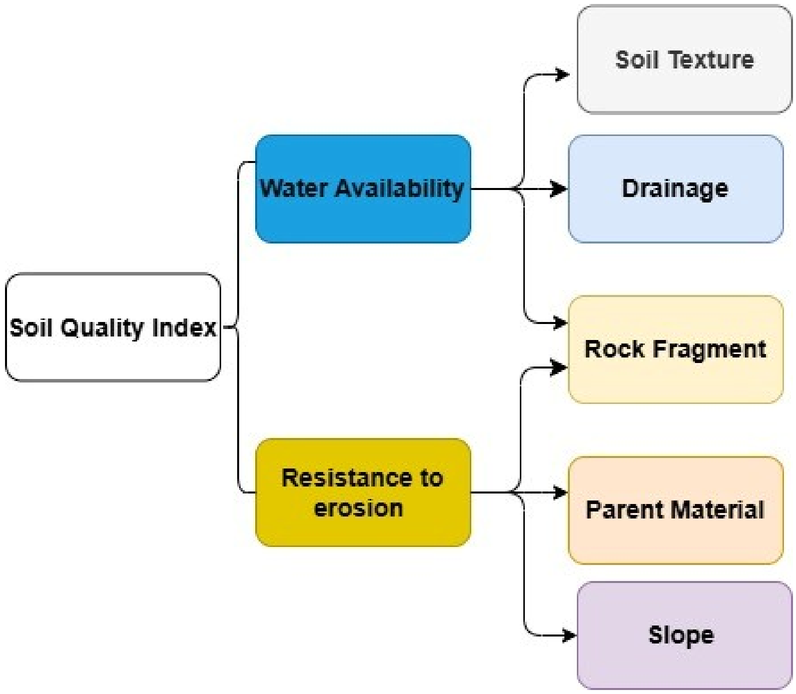

Figure 2. Flowchart illustrating the process of developed model.

Drainage and slope data were also extracted from ASTER digital elevation (DEM) with a spatial resolution of 30 m. The geological map was used to extract the predominant rock types in the study area, to classify rock characteristics, which were classified into three categories according to the degree of rock cohesion (resistant, moderately resistant, and weakly resistant). Using these characteristics seeks to identify and map environmentally sensitive areas (ESAs) based on distinct categories by gathering satellite data and GIS for desertification sensitivity assessment with an average rating between 1 and 2 within the model to weight layer procedure based on its influence and contribution to the desertification process. The individual indicators are listed in (Table 1). All indicator scores are combined into a final SQI value based on the following equation:

$$SQI = (\text{texture} \times \text{parent material} \times \text{rock fragment} \times \text{depth} \times \text{slope} \times \text{drainage})^{1/6}$$

The results of integrating soil quality as an adopted approach to link all interacting factors, through a set of synthetic maps that enabled the assessment of the current status of soil degradation in the study area and provided a prospective view of the extent of soil degradation leading to desertification in the semi-arid zone and its possible spread to the sub humid and humid zone, which is also threatened in the long term (Table 2).

Table 1. Classes and the corresponding weight assigned for the calculation of the SQI

Parameters	**Description**	**Classes**	**Quality index**
Parent material	Good resistant	Shale, Schist, Basic, Ultra-basic	1
	Moderate resistant	Conglomerate, Limestone, Marble, Granite, Rhyolite, Ignibrite, Siltastone, Sandstone	1.5
	Weakly resistant	Marl, Pyroclastic	2
Soil texture	Good	L, SCL, SL, LS, CL	1
	Moderate	SC, SiL, SiCL	1.2
	Poor	Si, C, SiC	1.6
	Very poor	S	2
Soil slope	Very gentle to flat	$< 6\%$	1
	Gentle	6–18%	1.2
	Steep	18–35%	1.5
	Very steep	$> 35\%$	2
Soil coarse fragment class	Very stony	$> 60\%$	1
	Stony	20–60%	1.3
	Bare to lightly stony	$< 20\%$	2
Drainage	Well drained	Low moisture content	1
	Imperfectly drained	High moisture content	1.2
	Poorly drained	The water level is permanently at a depth of more than 75 cm	2

Source: El Motaki (2024).

Table 2. Quantitative scores and qualitative classes of considered indicators (indices)

Class	Description	Range
1	High quality	< 1.13
2	Moderate quality	1.13–1.45
3	Low quality	> 1.46

Source: El Motaki (2024).

2.3. Assessing SQI

According to the MEDALUS approach, the results of the SQI, which determines the sensitivity of soil to degradation in the studied area, are based on the integration of the indicators according to the classes shown in Table 1, that are related to the soil characteristics, including Soil texture which is related to its erodibility and water retention capacity. Soils rich in silt have a high-water retention capacity, unlike sandy soils, which have a lower water retention capacity. Therefore, sandy soils are more prone to drought than clay soils because they retain less water, as they lose water very quickly during ploughing and exposure to the sun (Kosmas et al., 1998).

Soil depth was assessed through the morphological characteristics of vegetation cover, which reflects soil depth, as good vegetation cover can only grow on deep soil capable of retaining water and nutrients. Shallow soil cannot support vegetation cover. This is a result of soil structure being washed away due to erosion (Lee & Skogerboe, 1985). Soil resistance to degradation varies depending on the nature of the parent rock and the abundance of vegetation cover. Soils derived from fragile clayey rocks, which have low resistance, account for about 28% of the study area, which includes land cultivated with rain-fed cereals in the southern part of the study area. These areas are considered to be most vulnerable to degradation, as this soil cannot support any vegetation cover in dry years, despite its high productivity in normal and wet years (Kosmas et al., 1998).

Rock fragments rich soils, which are determined by > 6 mm over the soil surface or topsoil, play an important role in maintaining substantial quantities of stored water, particularly during dry years, and thus contribute to protecting land from desertification (Poesen & Lavee, 1994). The aspect of the slopes is one of the factors influencing the enhancement of morphodynamical formation (Li et al., 2019). It also determines the dynamics between the western slopes, which are exposed to humidity, and the southern and south-eastern slopes, which are more exposed to the sun and dryness (El Motaki, 2024).

The drainage index is an important factor in determining the amount of water that seeps into deep soil layers (Schaetzl et al., 2009), since well-drained soil loses water more quickly compared to poorly drained soil. In assessing the risk of degradation, salt accumulation was focused on as an indicator of the sensitivity of areas to degradation in relation to drainage quality (El Motaki, 2024). Three drainage categories were therefore identified, based on their impact on salt accumulation (good, moderate, and poor drained). Soil salinity results from the accumulation of salts in its components, which has negative impacts on soil quality and plant growth by reducing its physical and chemical properties (Monteleone et al., 2004). At the local level, the extent of salt concentration depends on various factors controlled by water, soil type, and total salt and sodium content. In areas that receive between 300 and 600 mm of rainfall, there is an increased concentration of salts in the soil leading to conditions that are unsuitable for plants and crops (Ferrara et al., 2012).

3. Discussing Findings

3.1. Soil Texture Index

The south part of the study area that corresponds to the semi-aid zone is characterized by clay soil that is subject to swelling and expansion during rainy periods when it becomes saturated with water, thus increasing surface runoff when it rains (**Figure 4**). While clay soils can retain water during wet seasons, and hence, poor drainage creates favorable conditions to various types of water erosion as a result of the breakdown of their texture, which leads to the deterioration of their structure. During the dry season, this soil is exposed to drought due to poor water permeability, thus becoming threatened with drought, resulting in poor quality soil.

In the northern part of the study area, which corresponds to the semi-humid zone, loamy soils predominate. This type of soil creates a balance between sand and clay, giving it moderate resistance to erosion. In terms of quality, it is classified as high quality. However, it is potentially subject to degradation due to intensive cultivation on steep slopes and poor land management. This contributes to the severity of degradation, as morphodynamic are widespread, particularly those associated with landslides, collapses and slides.

3.2. Soil Depth Index

According to MEDALUS' approach, three types of soil can be distinguished within the study area: deep soil, which exceeds 75 cm in depth, ranging between 80 and 90 cm, especially within the forest areas in the northern part of the study area. Then there is medium-depth soil, which ranges between 30 and 75 cm in depth. These categories are located in the Oudka and Ourtzagh areas, particularly on slopes that are exposed to overexploitation. Whereas shallow soil, which is less than 30 cm deep, dominates the southern and southwestern parts of the study area, with some forest clearings in the Oudka and Tiziran mountains in the northern part.

3.3. Parent Rock Index

Areas with soil composed of dolomitic limestone and marl are also widespread, particularly in the Numidian peaks, such as the Oudka, Beni Aider and Khazana mountains. Despite their low productivity in wet years, they provide significant amounts of stored water for plants, thus ensuring biomass production in dry years. These rocks are also resistant to the factors of degradation that affect the area, particularly water erosion. This category covers a small part of the study area, accounting for no more than 16%, and is located in the northern part of study area.

Areas with moderately resistant rock formations, which are the predominant type in the area, accounting for about 56%, are characterized by the predominance of flyschs, limestone formation represents important areas in the middle part of the study area. They are also characterized by medium-depth, medium-resistance soils, which are spread over medium-slope slopes.

Soil derived from fragile clayey rocks with low resistance constitute about 28% of the study area, which includes lands cultivated with rain-fed cereals in the southern part of the study area. These areas are more vulnerable to degradation, as this soil cannot support any vegetation cover in dry years, despite its high productivity in normal and wet years.

3.4. Rock Fragment Index

Stony soils are found in areas dominated by solid and medium- solid rocks, particularly in the northern part of the study area, and are associated with between 30% and 40% rock fragments. This is most clearly found in the Numidian area of the Oudka unit (Figure 3). In contrast, clay soils that are fragment-free, especially during cultivation, despite their high agricultural productivity (cereals in the Prerif zone) in normal and wet years, remain vulnerable to degradation in dry years in particular, due to their incapacity to support plants because of their poor drainage capacity (Ni et al., 2024). These areas are more prone to surface runoff, which increases the possibility of sediment production and loss more quickly (Figure 4). This corresponds to the southern part of the study area, where the average coverage is less than 10%, which is limited to the rows and remains very limited in area.

Figure 3. The role of rock fragments in protecting slopes from degradation in the Oudka unit (May 2024).

Figure 4. Areas with bare rock fragments in the southern part of Prerif area (June 2024).

3.5. Slope Aspect

The character of the slopes in the central Rif mountains and their southern margins reflects the predominance of south- and east-facing slopes, which represent more than 50% of the total area of the studied area, thus indicating that it is highly susceptible to water erosion.

The southern part of the study area is characterized by a very strong linear erosion on the slopes facing south and south-east, in contrast to the northern areas, with the central Rif domain, and above the western slopes, it is characterized by the predominance of various types of mass movements, especially during wet periods due to the availability of vegetation cover, which enhances permeability and thus contributes to the activation of near-surface runoff and the formation of near-surface and deep mass movements (Moore et al., 1998).

3.6. Drainage Index

The drainage of soil in the studied area varies between the north and south, where drainage was classified into three categories (good, medium, poor) based on the criteria adopted in the model The poor drainage category is the most prevalent in the study area and corresponds to the southern part, especially in areas where tertiary protrusions are widespread (Jabal al-Malha in Tissa) (Gartet et al., 2006).

The accumulation of salt on the soil surface in southern part of study area contributes to the forming of a dense, impermeable crust, thus preventing water from seeping into the soil. This negatively affects the soil's ability to transport water. In addition, it disrupts the balance of ions, as sodium replaces essential cations such as calcium and magnesium from soil particles, leading to a deficiency of plant nutrients, especially calcium, which contributes to the decline of vegetation in these areas and the surrounding environment (Gartet et al., 2006).

In the northern part of the study area, drainage conditions are associated with the prevalence of medium-permeability rocks and steep slopes that do not allow sufficient time for infiltration. Good drainage conditions in the southernmost part of the study area are also linked to rock conditions, as these margins are characterized by permeable solid rocks that allow for good water infiltration and are very limited in the study area (Bourg & Ajo-Franklin, 2017).

Climatic conditions associated with low rainfall (less than 500 mm annual average) and high temperatures exceeding 40 °C, especially in summer in the study area, lead to the accumulation of salts, particularly in clay soils which increases the difficulty of water infiltration as a result of occupying the spaces between soil particles, reducing pore space and increasing soil density (Wang et al., 2018). This pressure leads to poor water drainage, and thus increased surface runoff.

4. Validation and Results

Based on the application of the Environmentally Sensitive Areas (ESAs) approach, the susceptibility of soil to degradation was determined using the SQI, which integrates a range of variables related to soil characteristics (structure, depth, bedrock, rock fragments, slope and drainage), as one of the indicators used to classify these areas. Based on the equation used in this context, the SQI was determined based on its resistance to erosion in order to assess its sensitivity to degradation. It was observed that most areas in the northern part of the study area (Figure 5), accounting for 36% of the total area, are of high quality (Table 3). This soil is found in forested areas, which protect it and help it adapt and enhance its resistance to degradation, as it is highly fertile and has a high-water retention in soil depths exceeding 80 cm.

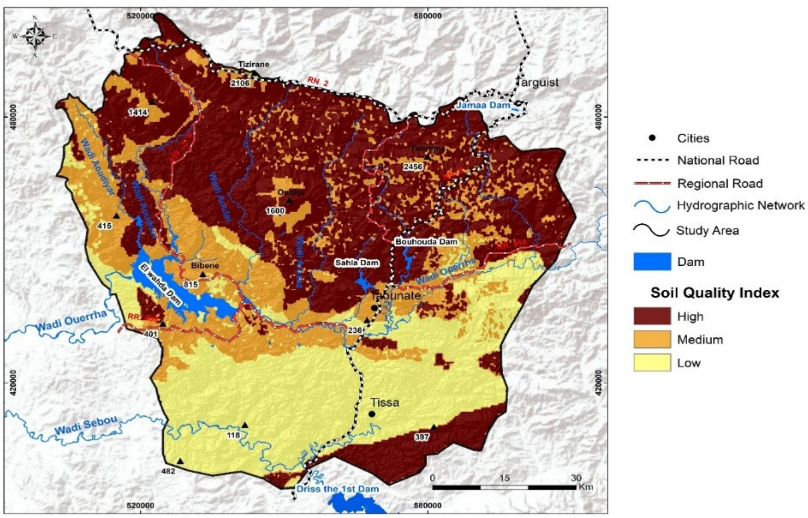

Figure 5. Correlation Coefficients between Quality Indices.

The middle and some northernmost areas of the study area are characterized by medium soil quality, giving them medium resistance, covering about 35% of the area (Table 3). This is due to the violent dynamics of this area and also to the severe loss of vegetation cover as a result of continuous deforestation to expand agricultural areas. This has contributed to making it moderately sensitive to degradation.

Table 3. The spatial distribution of the SQI in the study area

Class	Quality	Range	Areas (%)
1	High	< 1.30	36
2	Medium	1.13–1.45	35
3	Low	> 1.46	29

As for the poor-quality category, it constitutes about 29% of the total area of the study area (Table 3) and occupies large areas in the southern part. It is highly susceptible to degradation due to a combination of factors, such as its low water storage capacity due to its high clay composition, especially in climatic conditions characterized by successive dry years. It is also characterized by low resistance to erosion due to the prevalence of fragile clayey rocks.

5. Conclusion

The SQI was calculated using the MEDALUS approach, it can be applied as an effective tool for assessing soil quality, considering various soil parameters and giving the most consistent results. The results clearly show the impact of overexploitation on the slopes, and forest clearing, and climatic factors manifested in successive dry years, on soil quality. Soil quality indexing involves a three-step process: 1) identifying a set of indicator data; 2) converting the indicators into weighted values; and 3) integrating all indicator scores into a final SQI value. This method has made it possible to monitor changes in soil quality across various landscapes under different land uses. This approach can contribute to the development of accurate soil quality maps using spatially based information that is cost-effective and available. Areas such as forests, pastures and agricultural lands, slopes where human activities have led to soil degradation and agricultural land use transformation, need accurate and quantitative information sources to maintain their sustainable development.

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References

Baartman, J. E., van Lynden, G. W., Reed, M., Ritsema, C., & Hessel, R. (2007). *Desertification and land degradation: Origins, processes and solutions* (tech. rep.). DESIRE. Wageningen.

Bauer, S. (2016). The united nations and the fight against desertification: What role for the unccd secretariat? In *Governing global desertification* (pp. 93–108). Routledge.

Bourg, I. C., & Ajo-Franklin, J. B. (2017). Clay, water, and salt: Controls on the permeability of fine-grained sedimentary rocks. *Accounts of Chemical Research*, *50*(9), 2067–2074.

El Motaki, H. (2024). *Spatial modelling of environmental degradation of fragile areas in central rif mountains and their southern margins* [Doctoral dissertation, Ibn Tofail University] [In Arabic].

El Motaki, H., El-Fengour, A., Aissa, E., Madureira, H., & Monteiro, A. (2019). The global change impacts on forest natural resources in central rif mountains in northern morocco: Extensive exploration and planning perspective.

Ferrara, A., Salvati, L., Sateriano, A., & Nolè, A. (2012). Performance evaluation and cost assessment of a key indicator system to monitor desertification vulnerability. *Ecological Indicators*, *23*, 123–129.

Gartet, A., Gartet, J., & García, C. C. (2006). Exploitation des salines au massif diapirique de tissa et impacts environnementaux: Prérif central, maroc septentrional. *Papeles de Geografía*, (44), 23–38.

Hatfield, J. L., Antle, J., Garrett, K. A., Izaurralde, R. C., Mader, T., Marshall, E., Nearing, M., Robertson, G. P., & Ziska, L. (2020). Indicators of climate change in agricultural systems. *Climatic Change*, *163*(4), 1719–1732.

Imam, F. E., Smiraglia, D., Pulina, A., Assennato, F., Raparelli, E., & Seddaiu, G. (2025). Desertification risk: Bibliometric analysis and future research directions. *Land Degradation & Development*.

Kosmas, C., Danalatos, N., Poesen, J., & Van Wesemael, B. (1998). The effect of water vapour adsorption on soil moisture content under mediterranean climatic conditions. *Agricultural Water Management*, *36*(2), 157–168.

Kosmas, C., Karamesouti, M., Kounalaki, K., Detsis, V., Vassiliou, P., & Salvati, L. (2016). Land degradation and long-term changes in agro-pastoral systems: An empirical analysis of ecological resilience in asteroussia-crete, greece. *CATENA*, *147*, 196–204.

Laaribya, S., & Alaoui, A. (2025). Spatio-temporal trends and climate change impacts on land cover dynamics in talassemtane national park, morocco, using artificial intelligence and google earth engine. *Journal of Sustainable Forestry*, *44*(6), 289–318.

Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development*, *12*(6), 519–539.

Lee, C., & Skogerboe, J. (1985). Quantificiation of erosion control by vegetation on problem soils.

Li, M., Shi, X., Shen, Z., Yang, E., Bao, H., & Ni, Y. (2019). Effect of hillslope aspect on landform characteristics and erosion rates. *Environmental Monitoring and Assessment*, *191*(9), 598.

Monteleone, M., Gatta, G., Giuzio, L., La Rotonda, P., & De Caro, A. (2004). Effect of leaching on salt accumulation in the soil under brackish water irrigation. *Proceedings of the International Workshop and Special Session on Management of Poor Quality Waters for Irrigation*.

Moore, H., Fox, H., Harrouni, M., & Alami, A. E. (1998). Environmental challenges in the rif mountains, northern morocco. *Environmental Conservation*, *25*(4), 354–365.

Ni, S., Shi, B., Zhao, J., Wang, D., Zhu, L., Wang, J., & Cai, C. (2024). A review of impacts of soil rock fragments on slope erosion: Mechanism and processes. *Land Degradation & Development*, *35*(10), 3226–3243.

Poesen, J., & Lavee, H. (1994). Rock fragments in top soils: Significance and processes. *CATENA*, *23*(1–2), 1–28.

Salvati, L., Mavrakis, A., Colantoni, A., Mancino, G., & Ferrara, A. (2015). Complex adaptive systems, soil degradation and land sensitivity to desertification: A multivariate assessment of italian agro-forest landscape. *Science of the Total Environment*, *521*, 235–245.

Schaetzl, R. J., Krist, F. J., Stanley, K., & Hupy, C. M. (2009). The natural soil drainage index: An ordinal estimate of long-term soil wetness. *Physical Geography*, *30*(5), 383–409.

Sivakumar, M. V. (2007). Interactions between climate and desertification. *Agricultural and Forest Meteorology*, *142*(2–4), 143–155.

Wang, Y., Deng, C., Liu, Y., Niu, Z., & Li, Y. (2018). Identifying change in spatial accumulation of soil salinity in an inland river watershed, china. *Science of the Total Environment*, *621*, 177–185.