Identifying Optimal Reforestation Sites in Erbil Governorate Using GIS and Remote Sensing

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Abstract
The Kurdistan Region of Iraq, particularly Erbil Governorate, is undergoing rapid land-use changes threatening its mountain oak forests and semi-arid ecosystems. To identify the best areas for large-scale reforestation and climate-resilient landscape management, this study employs multi-sensor remote sensing, geographic information systems (GIS), field surveys, and multi-criteria decision analysis (MCDA). Airborne and topographically corrected Sentinel-2 (10 m), and Landsat-8 (30 m) imagery (for 2024) was classified using a hybrid approach combining maximum likelihood and mean K (92% accuracy and kappa coefficient 0.87), supplemented by additional data from ASTER-DEM (such as slope, relative elevation, and topographic). Six reforestation criteria (Precipitation, Slope, Aspect, DEM, Land surface Temperature(LST), and Normalized Difference Vegetation Index (NDVI) were weighted using the Analytic Hierarchy Process(AHP)and integrated into the MCDA framework to generate suitability maps at 10-meter resolution. Spatial and temporal assessments show gradients in rainfall (446 mm/year in Shaqlawa to 1397 mm/year in Mergasur) and midsummer LST (below 35°C to above 50°C). Higher elevations are inversely related to LST (mean correlation coefficient r = -0.74) and positively associated with the NDVI vegetation index, whereas NDVI and ground surface temperature are generally negatively correlated. Forest cover reaches 67% in Mergasur and drops to 22% in urban Shaqlawa. Suitability modeling indicates that north- and east-facing mid-elevation wetlands in Mergasur and northern Soran are ideal for afforestation. The steep, drought-prone slopes of Choman and Rawanduz require terrace construction and the planting of cold-resistant species, whereas Shaqlawa's urban hotspots require drought-tolerant plants and urban afforestation. Overall, the workflow demonstrates that integrating Sentinel-2 and Landsat data with physiographic, climatic, and socioeconomic layers can support evidence-based afforestation in mountainous areas with limited data. Implementing location-specific strategies, such as appropriate species selection, slope stabilization, and continuous remote-sensing monitoring, can enhance carbon sequestration, reduce erosion, and strengthen environmental resilience in Erbil Governorate.

Keywords: GIS, Precipitation, NDVI, Aspect, Slope, DEM, and Erbil Province.

1Introduction

.Reforestation, as described by Nave, Domke [1] , involves planting trees in areas that have been deforested or degraded. It is essential for restoring ecosystems, absorbing carbon, and enhancing biodiversity [1]. The Middle East, especially the Kurdistan Region of Iraq (KRI) and Erbil, suffers from significant environmental challenges due to rapid urbanization, agricultural growth, and socio-political instability, leading to land degradation and deforestation [2].The global environmental crisis, driven by deforestation, climate change, and ecosystem decline, calls for sustainable environmental practices worldwide [3, 4]. Many countries employ remote sensing tools for reforestation efforts; for example, Brazil uses satellite imagery to monitor deforestation and identify degraded lands in the Amazon [5]. Similarly, China's "Grain for Green" program utilizes remote sensing to convert marginal farmland into forests [6], and Ethiopia extensively applies geographic information systems and remote sensing through its Green Legacy project [7]. Reforestation helps prevent soil erosion and flooding and slows further deforestation [8]. Recently, the Kurdistan Regional Government in Iraq launched tree-planting initiatives, especially around Erbil [9]. Reforestation provides significant environmental and economic advantages, but effective forest management is crucial to justify the investment [10]. Choosing suitable sites is a vital first step, as environmental and ecological factors greatly influence the success of the new forest [11, 12]. Incorporating advanced technologies such as geographic information systems (GIS) and remote sensing can greatly enhance the analysis of optimal sites [13-15]. The reasons for restoring degraded forests include timber, livestock, agriculture, mountainous terrain, limited arable land, government initiatives, national parks, and historical external influences [16-18]. Consequently, this study aims to determine the best sites for afforestation in Erbil Governorate [19, 20]. The decline in forest resources due to agricultural expansion over the past 25 years aligns with the national trend [21, 22], and this decline is likely to accelerate without conservation efforts. Reforestation sites located away from densely populated areas and within freshwater zones should be prioritized because of soil and water depletion [23-25]. Identifying suitable areas requires evaluating physical, climatic, and accessibility factors [26]. Gentle slopes (less than 15%) are ideal, as steeper slopes increase erosion [27]. Slope orientation impacts sunlight and moisture, with north-facing slopes often being more suitable in arid regions [28]. Areas between 500 and 1500 meters above sea level are preferred [26]. Land availability should be evaluated using land-use planning and remote sensing [29]. Proximity to roads lowers logistical costs [30]. Key weather criteria include annual rainfall exceeding 500 mm and temperatures between 15 and 30°C [31]. Low silt content is preferred to prevent soil degradation [32]. Geospatial analysis helps identify suitable areas of 5,000 acres or more for reforestation [26 .[

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Historically, Erbil Governorate has worked to reforest areas that have been turned into steppes and scrublands where forests once thrived [33]. Reforestation and afforestation are becoming more important worldwide due to the environmental impacts of deforestation [34]. In developing countries, clearing land for agriculture results in biodiversity loss and environmental damage [35]. Human activities such as unsustainable farming expansion, conflict, forest land conversion, land degradation, and population growth have contributed to forest decline and the loss of ecosystem services [34-37]. Climate change, including drought, also harms forest productivity and cover [20, 38]. Still, efforts to reforest have been limited [39, 40]. Reforestation sites should be chosen based on scientific analysis to ensure efficient use of trees and proper site restoration [41, 42]; otherwise, reforested areas will not develop naturally [42]. This study aims to identify the best sites for reforestation and afforestation in Erbil by examining environmental factors, analyzing forest distribution using remote sensing and GIS, generating an environmental site assessment map, and using a digital elevation model and multi-criteria analysis to classify potential forest sites.

The results will offer valuable insights to guide reforestation and afforestation, considering the region's unique spatial and natural conditions. The study will also evaluate the features of natural forests in Erbil using remote sensing data and other sources. This research seeks to answer these questions: (a) Which areas are most suitable for forest development in Erbil? (b) What are the best sites for reforestation and afforestation? (c) What methods and analysis levels are used to evaluate potential forest lands in Erbil? (d) Which strategies are most effective for implementing reforestation in Erbil? Overall, this research will demonstrate the best methods for reforestation in Erbil.

2. Materials and Methods

2.1. Study Area

Erbil Governorate is located in northern Iraq, between latitudes 35°45'N and 37°N and longitudes 43°E and 45°E [43]. Covering roughly 14,471 square kilometers, it features varied terrain including plains, hills, and valleys. Key landmarks include the UNESCO World Heritage Site, the Erbil Citadel, and the Bradost and Korek mountain ranges [44].The city of Erbil, the capital, is an ancient settlement over 6,000 years old and one of the world's oldest continuously inhabited cities [44].

The governorate links Iraq with Turkey, Iran, and Syria, serving as an essential commercial hub [43]. Located in the (KRI), Erbil's natural environment is diverse, with different topography, climate, soil types, and vegetation. Its landscape supports a range of plant life, from forests in the highlands to grasslands in the lowlands, with annual rainfall averaging 400–800 mm, especially in winter, which fosters agriculture and native flora [45].The area's mountains, plains, and valleys formed through ancient tectonic activity and

erosion, influencing local climate. Higher regions tend to be cooler and wetter than the arid plains. Soil varies from calcareous in the plains to nutrient-rich in the mountains [46].
Erbil has a semi-arid climate, with hot, dry summers and mild, wet winters, significantly impacting land use and agriculture, necessitating measures to mitigate rainfall variability [47]. The region’s ecological diversity underscores the importance of sustainable practices to maintain its health [48]. Recent research highlights the vital role of ecosystems in promoting biodiversity and addressing climate change [46]. Vegetation includes oak forests in highlands and degraded woodlands affected by human activity [45]. Urbanization and economic growth are driving a shift from traditional agricultural land use to residential and commercial developments [49].

2.2. Material

2.2.1. Sentinel-2 Data

Sentinel-2, part of the European Space Agency's Copernicus program, provides high-resolution multispectral images (up to 10 meters). Its red-edge and near-infrared bands are particularly important for assessing vegetation health and studying natural phenomena, making it an essential tool for landscape monitoring and accurate vegetation assessment [50].

2.2.2. Landsat Datasets

Landsat's Image, especially the Landsat 8 Operational Land Imager (OLI), offers valuable medium-resolution (30-meter) data for studying long-term vegetation changes and mapping land use and land cover. This free and open-source data is widely utilized in vegetation indices, like the National Vegetation Index (NDVI), which is essential for tracking reforestation and spotting deforestation patterns [51]. Data collection is the first stage of our study, and obtaining suitable datasets is crucial for accurate results (Burke et al., 2021). We relied on two main data sources: satellite imagery and ground survey data (Yeh et al., 2020). The study area was Erbil Governorate, where we used a classification method on the satellite imagery dataset. We also relied on the local forestry department for ground survey data, including tree measurements and species identification. This enhanced data quality and included thorough quality checks prior to the initial analysis (Alam et al., 2020).

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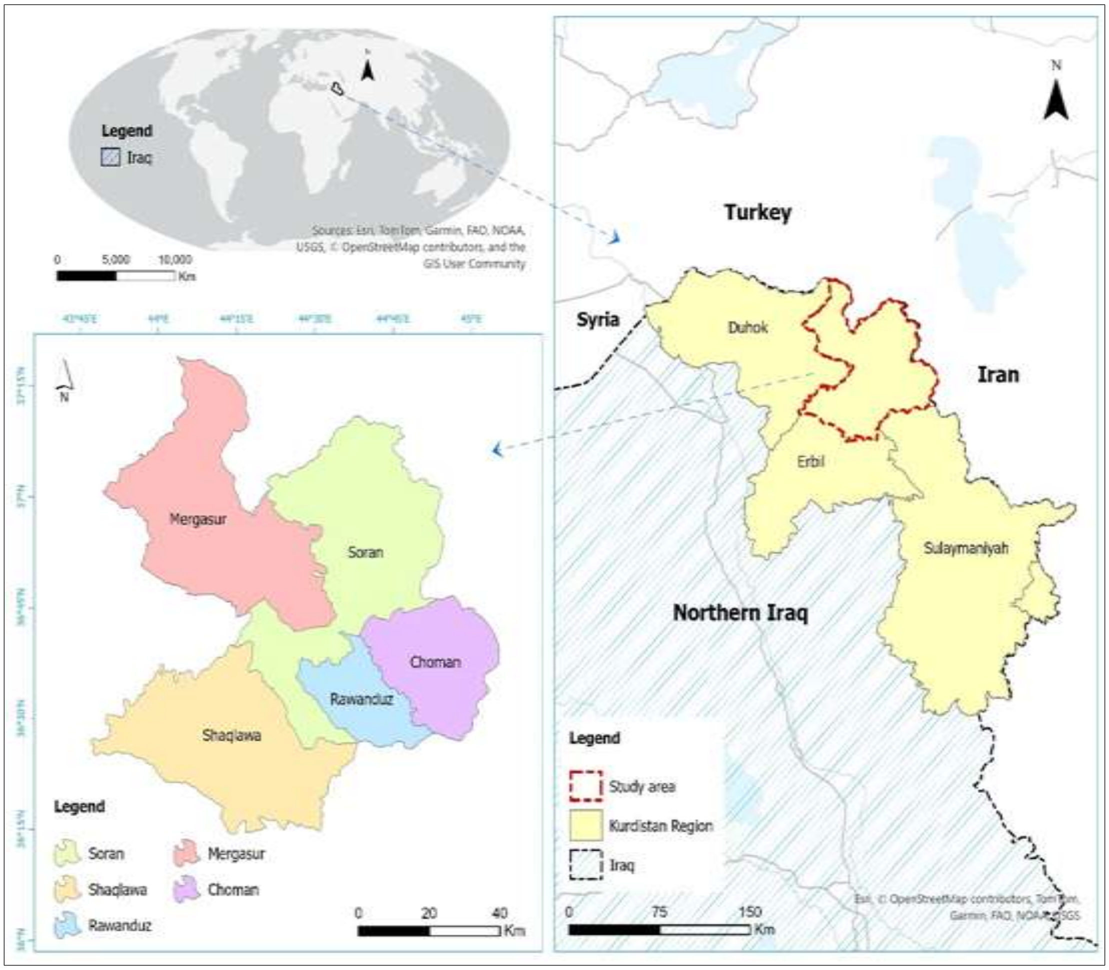

Figure 1: (A) Location map of the study area in the world, (B) DEM map for the study area in Iraq, (C) Five districts

2.3. Methodology

Preprocessing is a critical step in remote sensing analysis [52]. Correction removes the topographical influence on the image, as the target area is very mountainous [53]. Image classification is the process of extracting information from a digital image into a controllable format and is one of the most widely used techniques in remote sensing [54].

Site Selection Criteria: Five main criteria were collectively established to choose the best sites for reforestation in Erbil, including Six reforestation criteria (Precipitation, Slope, Aspect, DEM, Land surface Temperature and Normalized Difference Vegetation Index (NDVI) [55].

2.3.1. Data Processing and Validation

Collecting field data on soil and vegetation is essential for accurate remote sensing and land cover mapping [56]. Research shows that integrating advanced remote sensing techniques with field data improves classification accuracy and minimizes the need for extensive field data collection [57]. For example, combining Sentinel-1 and Sentinel-2 data contributes to the creation of effective training data for land cover mapping [58], significantly boosting accuracy (up to 98.25%) by merging spectral and radar data, with machine learning classifiers such as Random Forests performing better [57]. Remote sensing tools like Google Earth and vegetation indices such as NDVI are widely used to identify degraded lands and monitor their changes. I utilize high-resolution Sentinel-2 imagery as a crucial source of information for detecting vegetation loss, which is vital for selecting reforestation sites [59].

2.3.2. Accuracy assessment using confusion matrices and validation points.

Accuracy assessment is an essential step in evaluating the performance of classification models in remote sensing. It allows researchers to determine how well a classified map aligns with real-world field data [60, 61]. Key metrics include overall accuracy, product accuracy, user accuracy, and the kappa coefficient, each assessing different aspects of classification reliability [62, 63]. These metrics depend on checkpoints, collected from field data or high-resolution images, to build a confusion matrix and verify the accuracy and representativeness of the results for the study area[61, 62]. To enhance assessment accuracy and reduce bias, checkpoints should be carefully chosen and spatially well-distributed, with a sufficient sample size [63, 64].These methods are vital for validating land cover classifications, especially in reforestation studies that track vegetation changes and identify areas needing intervention [60, 62]. Specifically, field checkpoints (tree presence/absence, species identification, and basic tree measurements from the local forestry department) were georeferenced and overlaid on the satellite-derived layers (e.g., NDVI, elevation and precipitation). For each checkpoint, we extracted the corresponding pixel values from the remote sensing layers and compared them with the observed field condition. We then evaluated whether checkpoints with healthier trees/appropriate species and stronger growth indicators were predominantly located in the "high/very high suitability" classes, while poorer or degraded field conditions fell within the "low suitability" classes. This procedure is now described step-by-step in the Validation subsection, along with the total number of checkpoints used and the agreement statistics.

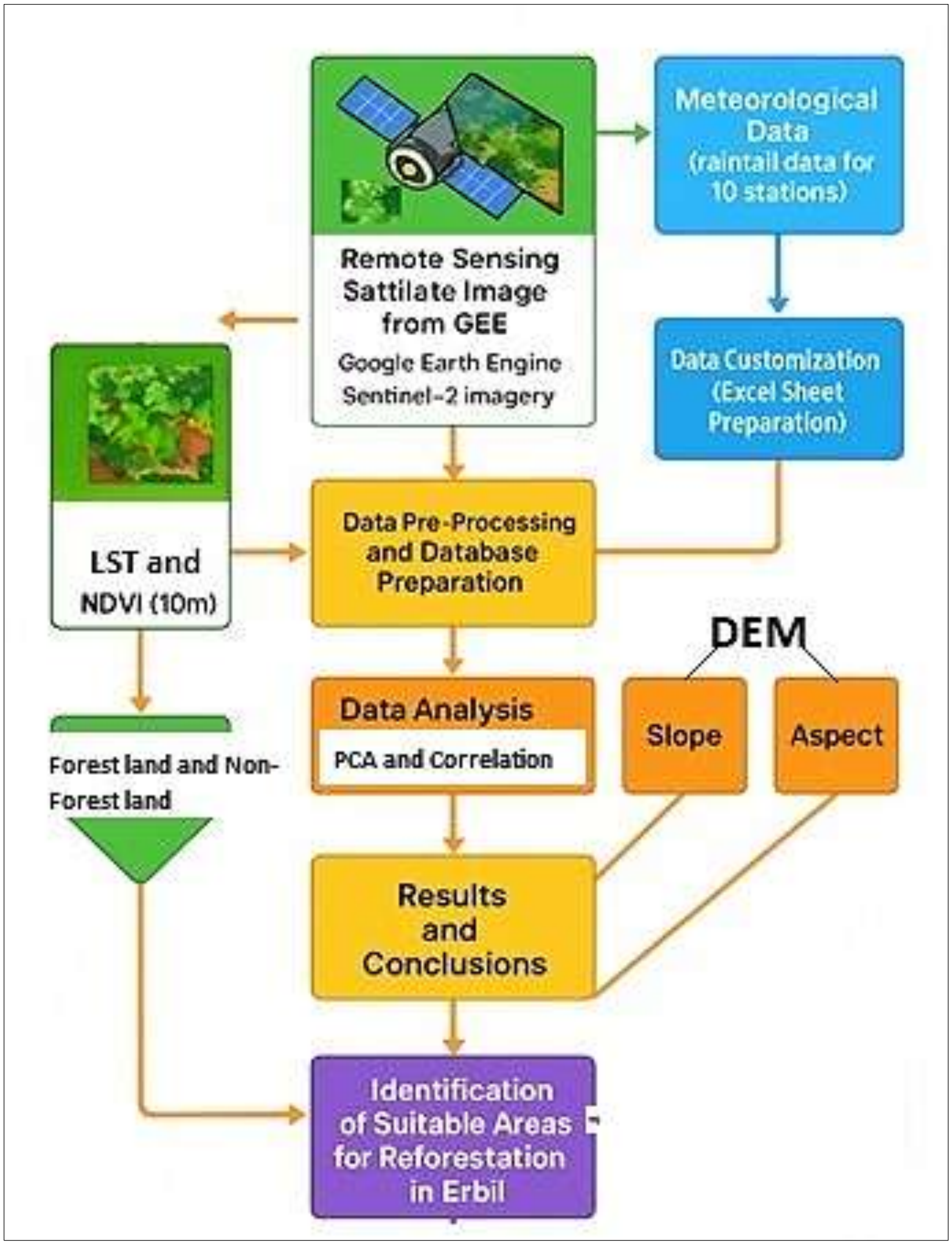

Figure 2: Flow diagram showing the methodology.

2.3.3. Multi-Criteria Decision Analysis (MCDA)

Environmental factors are crucial in determining forest success and sustainability, greatly influencing land management decisions related to reforestation. Among these factors, soil quality and slope are key in affecting erosion and drainage rates, which directly impact soil stability and its capacity to support vegetation [65]. Additionally, climatic factors like rainfall patterns and average temperatures are essential in determining which plant species can thrive in a specific area and influence physiological processes such as photosynthesis

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and transpiration, vital for plant survival and growth [66-68]. Therefore, understanding and assessing these environmental factors is critical for making informed land management and reforestation decisions that optimize both environmental and practical outcomes. Multi-criteria decision analysis (MCDA) is a systematic method used to evaluate and rank conflicting and competing criteria. It is especially important in environmental and spatial planning, where decisions must balance multiple considerations[65].When analyzing site suitability for reforestation, choosing appropriate criteria is essential, as it directly influences the achievement of environmental and operational goals [69]. This approach was utilized to identify the most suitable location for reforestation in this study.

2.3.3. Spectral Indices

2.3.4. Normalized Difference Vegetation Index (NDVI)

The NDVI index is calculated based on the reflectance of the red (Red) and the Near-Infrared (NIR) bands of the Landsat images, using formula 1, as follows:

$$\mathbf{NDVI} = \frac{NIR - Red}{NIR + Red} \quad \mathbf{1}$$

Theoretically, NDVI values range from −1.0 to +1.0. However, the typical range for NDVI from vegetation and other earth surface materials is roughly −0.1 (where NIR is less than Red) for bare or non-vegetated areas, and up to 0.9 for dense vegetation cover. NDVI values tend to increase with more green biomass, positive seasonal changes, and favorable conditions such as abundant rainfall [70, 71].

3. Results and Discussion

3.1. Precipitation and its relation to Afforestation:

Figure 3 shows the distribution of average annual rainfall across Erbil Governorate from 1997 to 2024. This image clearly demonstrates how rainfall varies in different parts of the governorate. It is important to note that rainfall varies greatly between areas, ranging from about 446 mm/year to nearly 1397 mm/year. This wide variation has significant effects on environmental planning and resource management.

The highest rainfall, over 1300 mm/year, is mainly found around the Mergasur area. This high level of rainfall makes this region ideal for large-scale planting projects, as there is enough moisture to support tree growth without needing much intervention. This natural setting offers a great chance for ecosystem restoration and vegetation enhancement. In contrast, the Shaqlawa area, especially near the Bastura station, receives much less rainfall, with annual totals below 600 mm/year. This low rainfall suggests possible difficulties for reforestation efforts, as natural conditions might not support sustainable tree growth without additional water management. Activities such as rainwater harvesting and supplemental irrigation may be needed to help plants survive and grow. Climatic factors such as rainfall and temperature are critical determinants of ecological processes and land management strategies [68]. Rainfall variability significantly influences soil erosion, sediment transport, and siltation in rivers and reservoirs. For example, higher rainfall intensity can lead to more runoff and sediment entering water bodies, which worsens siltation [72]. Conversely, decreased or irregular rainfall can diminish vegetation cover, reducing natural protection against soil erosion [73]. Overall, the detailed spatial analysis in Figure 3 provides valuable insights for making informed

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decisions on targeted planting, helping to effectively use resources to restore a healthy and sustainable ecosystem in Erbil Governorate.

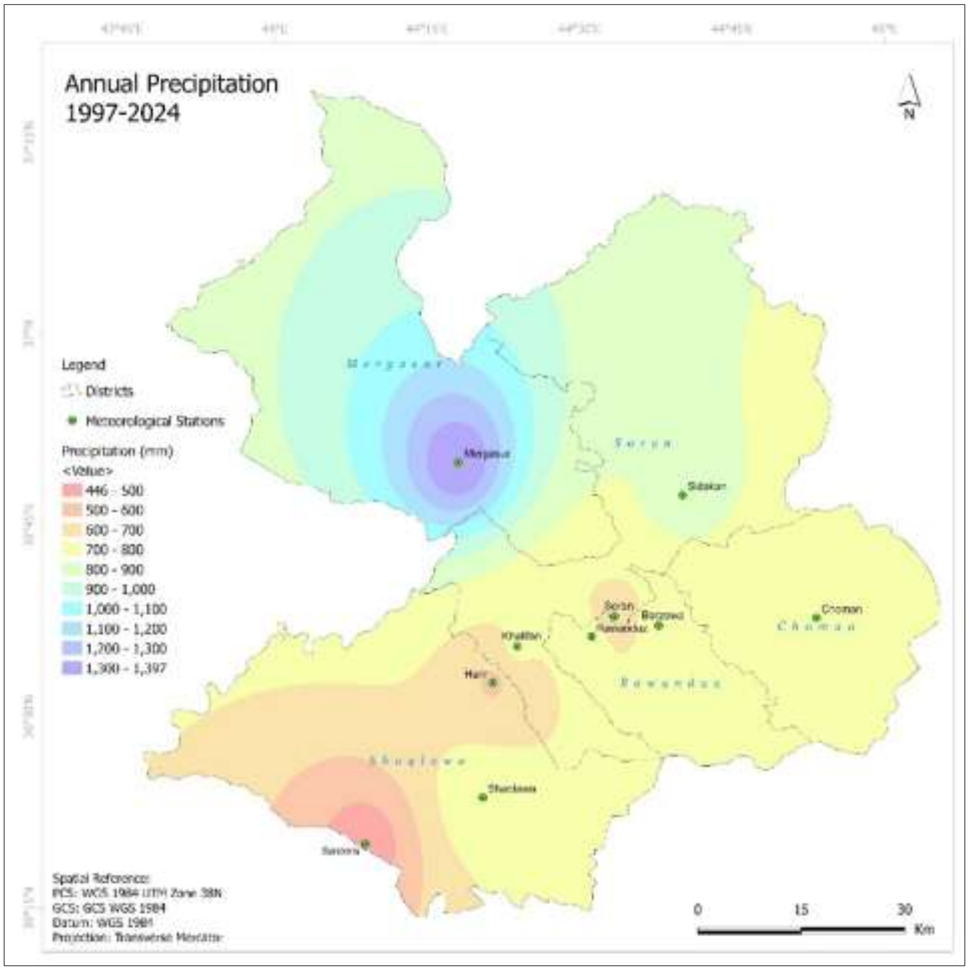

Figure 3. The spatial dispersion of yearly precipitation (mm/year) in Erbil from 1997 to 2024.

3.2. Topographical Characteristics (Aspect)

Figure 4 demonstrates the slope distribution in the study area, where color indicates the slope direction. Slope direction is vital for afforestation because it affects solar radiation and local climate, which subsequently influence plants' water needs. South- and west-facing slopes receive more sunlight, making them warmer and drier, thus requiring Drought-tolerant plants include oak forests dominated by Quercus aegilops, with Pistacia khinjuk and Crataegus spp. as common associates. Drought tolerant mountain taxa include Prunus microcarpa, a notable example in the Kurdistan highlands. Pinus brutia is also included as a regionally occurring Mediterranean pine adapted to hot-dry conditions.. Conversely, north- and east-facing slopes are cooler and wetter, which benefits forest establishment, especially in water-scarce regions. Combining slope data with the rainfall map (Figure 2) shows that humid northern areas, such as Mergasur and Soran , have north- or east-facing slopes, creating favorable conditions for tree growth. On the other hand, arid zones like Shaqlawa or parts of Harir District tend to have south- and southwest-facing slopes, adding challenges of low rainfall and high evaporation. Understanding slope direction helps identify the best locations for planting and allows for adaptation of tree species to local conditions. Shade-loving species do well on northern slopes, while drought-resistant species are better suited for sun-exposed southern and western slopes. Site preparation and water management techniques, such as terracing or drip irrigation, can be customized to each aspect to enhance the success of afforestation.

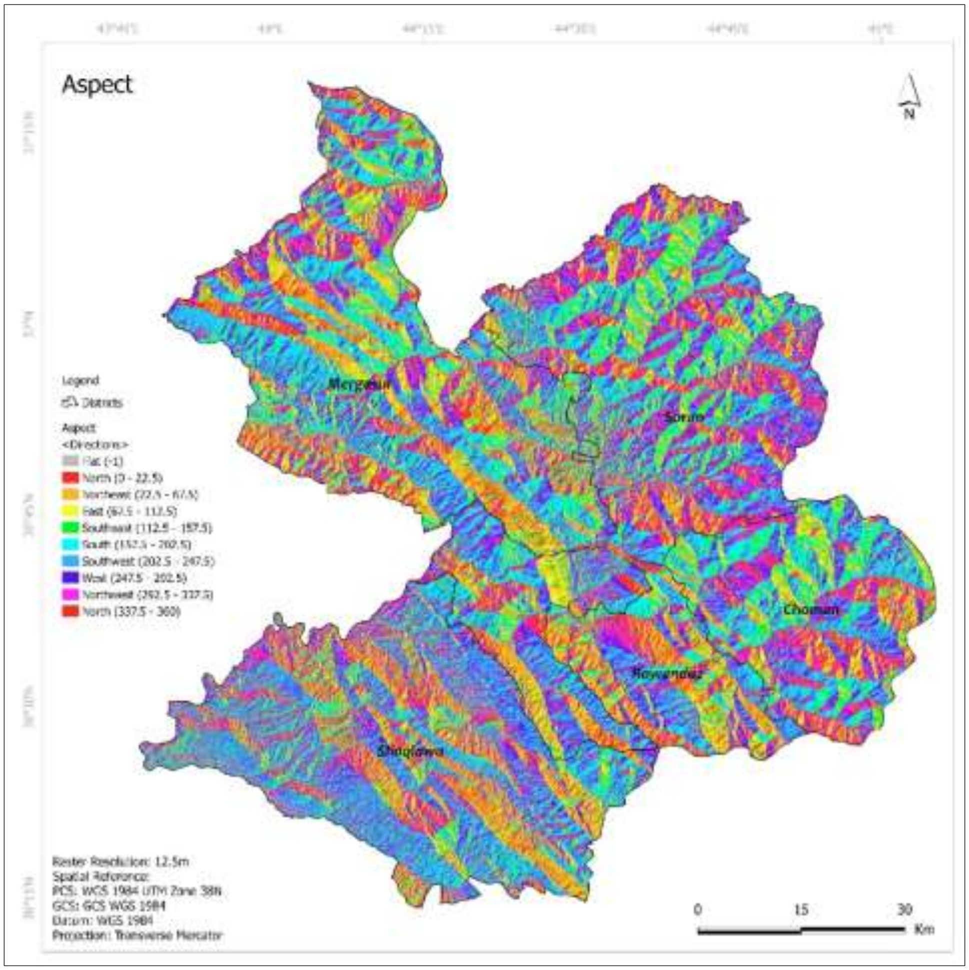

Figure 4. Map depicting the Aspect of the research site

Northern regions like Mergasur and Soran are especially important for afforestation due to their high rainfall. This abundant rain creates a moist, ideal environment for tree growth. Additionally, these areas have northern and eastern slopes that are particularly suitable for planting for several reasons. First, they provide high humidity, which is crucial for young trees. Second, these slopes receive less direct sunlight, helping to reduce moisture loss from soil and leaves. This limited sunlight creates a more moderate climate, lowering heat stress on young trees and improving their chances of survival and growth. Conversely, regions with less rain, such as Shaqlawa and Harir, face more challenges for afforestation.

These areas have southern and southwestern slopes that are harder to retain soil moisture because they are exposed to more sun each day. The extended sunlight causes rapid evaporation, decreasing moisture availability and making survival and growth more difficult for trees. Understanding how slope orientation interacts with climate is essential for successful afforestation. Selecting the right planting sites depends heavily on this relationship. Shade-loving trees that prefer humid, temperate conditions thrive on northern slopes where humidity is high and sunlight is limited. On the other hand, drought-tolerant and sun-loving species flourish on southern slopes, where sun exposure is abundant and humidity is low, allowing them to adapt to harsher conditions. In addition to choosing appropriate species, various techniques can help promote tree growth and conserve water. Terracing reduces water runoff and increases soil moisture absorption. Contour planting follows the natural lines of slopes to prevent soil erosion and retain water. Drip irrigation delivers water directly to the roots, minimizing evaporation and ensuring trees receive adequate moisture.

3.3. Digital Elevation Model (DEM) and its Implications for Afforestation

Figure 5 shows the (DEM) of the study area, a vivid visual representation of the variation and distribution of elevations across the region. This DEM reveals a wide range of elevations, from a low point of 288 meters above sea level to an impressive high of 3,619 meters. Elevation, as illustrated by the DEM, is a crucial and highly influential factor in the strategic planning of afforestation and reforestation operations. This is due to the profound impact of elevation on a variety of critical environmental factors, including prevailing climatic conditions, soil characteristics, and the plant species that can thrive under these specific conditions.

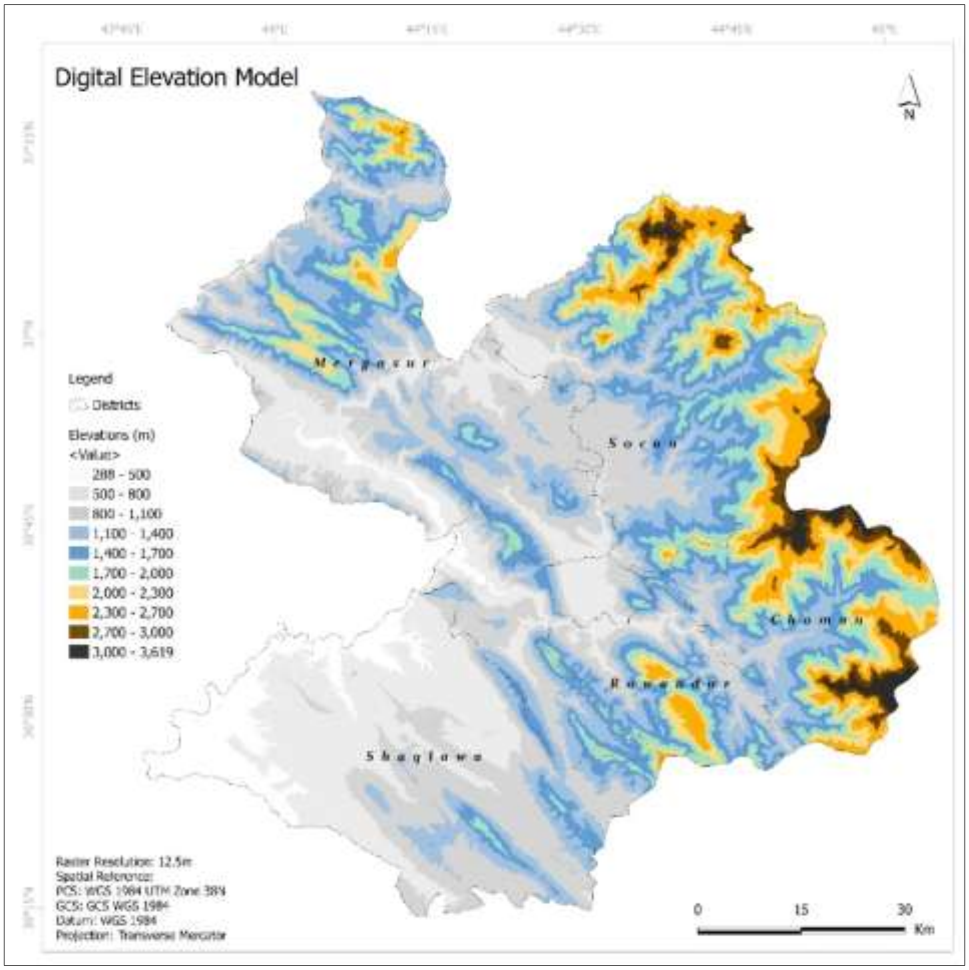

Figure 5. Digital representation of the elevation model (DEM).

High-elevation areas are characterized by colder climatic conditions, often-higher rainfall, and steeper terrain. These combined environmental factors significantly influence tree growth and distribution. Specifically, the DEM map indicates that the highest elevations are located in the northeastern part of the study area, particularly in Choman and parts of Soran. These areas, with elevations exceeding 2,700 meters, are particularly well-suited for planting cold-hardy tree species that can withstand the harsh climatic conditions at these altitudes. However, it is also essential to address soil stability challenges in these high-altitude regions by implementing appropriate soil conservation techniques to ensure the long-term survival of newly planted trees. In contrast, low-lying areas, below 800 meters, have entirely different climatic characteristics. These areas include Shaqlawa and parts of Rawanduz. Higher temperatures and lower rainfall characterize these low-lying regions compared to the higher-altitude areas. Furthermore, these low-lying areas are often more accessible and offer less rugged terrain, facilitating afforestation efforts. Afforestation efforts in these areas can contribute to ecosystem restoration and soil conservation, as well as enhance resilience to the impacts of climate change. In addition, with careful

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management, these low-lying areas can support the successful cultivation of drought-tolerant tree species, coupled with effective water management strategies to ensure optimal growth. Finally, mid-altitude areas, ranging from 1,000 to 2,000 meters, offer a valuable balance between temperature and humidity. These areas include Mercosur and parts of Rawanduz. This balance makes these regions ideal for cultivating a variety of native tree species, contributing to the preservation of regional biodiversity. These areas also serve as essential transition zones for reforestation efforts, facilitating the transition between tree species suited to high- and low-altitude regions, thereby promoting the overall sustainability of the ecosystem.

3.4. Land surface temperature (LST)

Figure 6 illustrates the spatial and temporal distribution of ground surface temperature (LST). The Choman region is characterized by a significant decrease in temperature (below 40°C, and sometimes below 35°C), indicating good plant health, high altitude, or a favorable climate that supports plant stability and ecosystem resilience. The average ground surface temperature in Soran and Rawanduz suggests moderate environmental conditions that offer promising opportunities for environmental projects. The variation in ground surface temperature provides valuable insights for planning and implementing afforestation efforts. The high temperatures in Shaqlawa and Mergasur indicate potential environmental vulnerability resulting from low forest cover, intensive land use, or urban expansion, necessitating urgent environmental intervention through strategic planning and urban afforestation to reduce temperatures, mitigate heat stress, and restore ecological balance. The moderate conditions in Soran and Rawanduz are ideal transitional zones for initiating afforestation programs, which help mitigate high temperatures, improve plant health, and promote long-term environmental sustainability. The lower-temperature areas in the Choman region indicate relatively stable environmental conditions and established vegetation, making them suitable for ongoing conservation efforts to preserve existing forests, ecological health, and local biodiversity through sustainable management and conservation practices. The map's color gradient, measured in July and August 2024, illustrates temperature variations: blue (below 35°C), yellow (35–45°C), pink (45–50°C), and dark pink (above 50°C).

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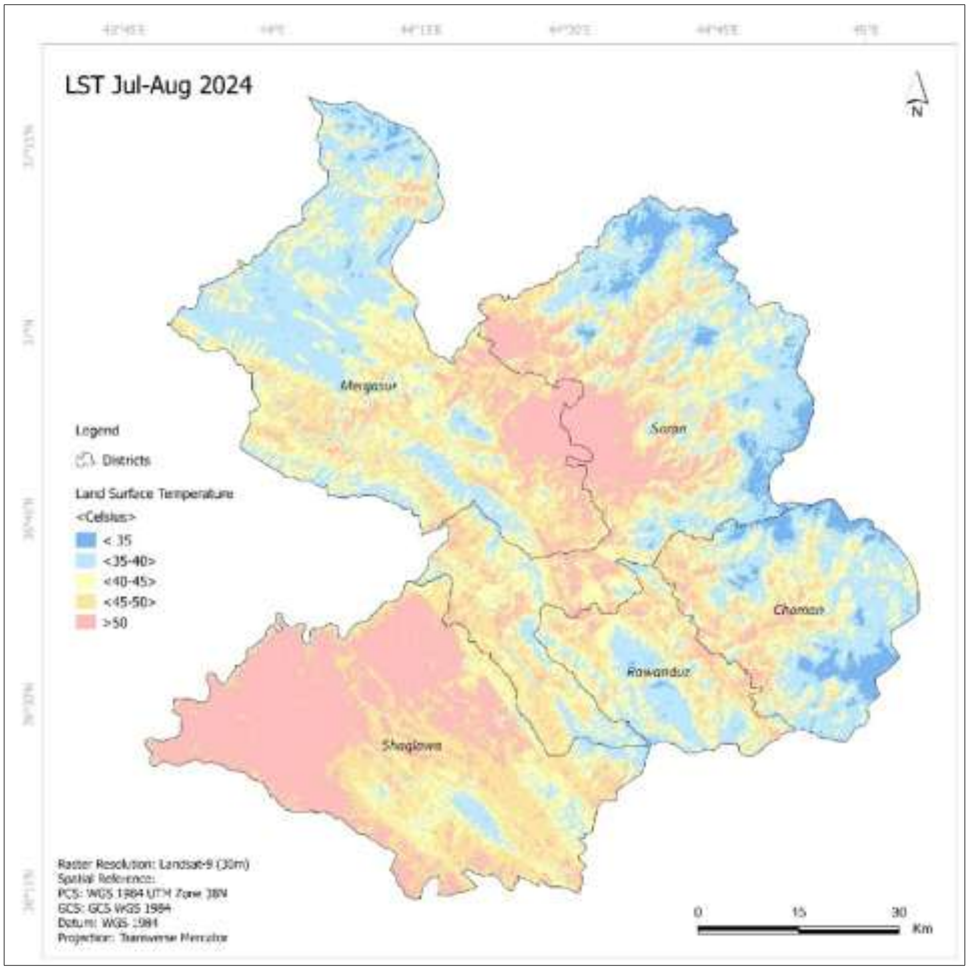

Figure 6. Spatio-temporal pattern of LST for the research site.

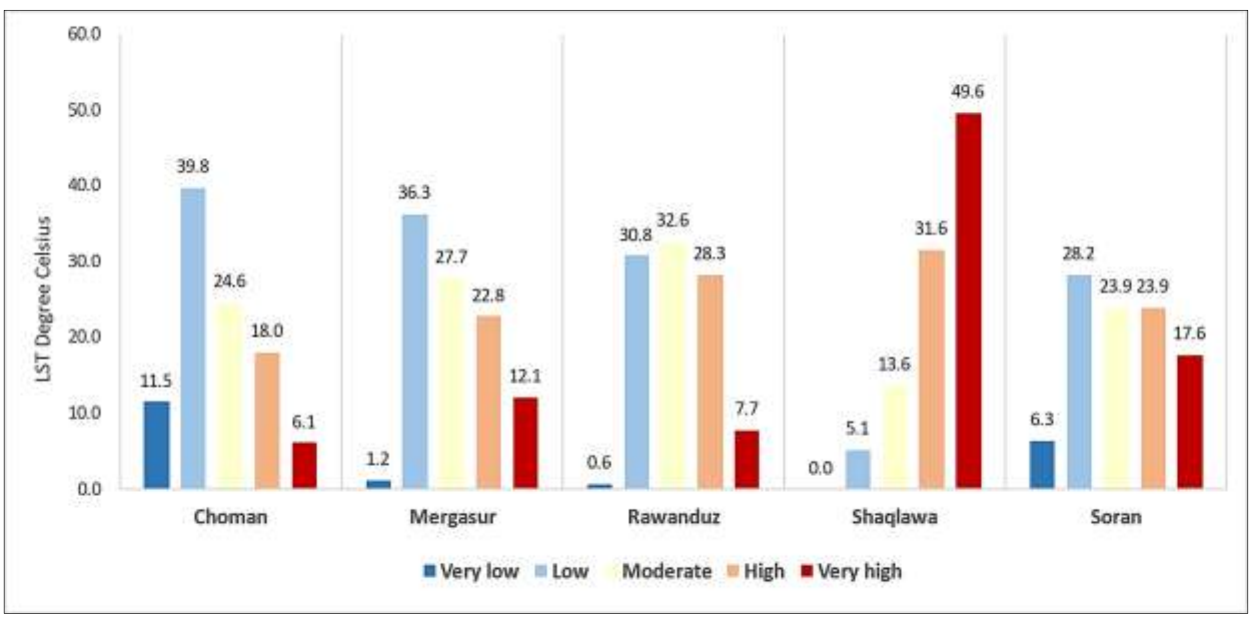

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Figure 7. The Spatio-Temporal pattern of LST of the research site.

The data shows a significant and clear spatial variation in (LST) within the selected study area, heavily influenced by various environmental and topographical factors. Shaqlawa and large parts of the Mergasur region recorded the highest ground surface temperatures in the study, exceeding 45°C in large areas and even surpassing 50°C in some places. This sharp increase in temperature is mainly due to the sparse vegetation cover in these areas, land degradation, both agricultural and non-agricultural, and ongoing urbanization. These factors significantly boost localized heat buildup, leading to environmental pressures, hindering plant and tree growth, and threatening the long-term environmental, agricultural, and economic sustainability of the region. These distinct and varied temperature differences directly affect soil structure and composition, groundwater infiltration, and sediment transport. In hotter, drier regions, evapotranspiration increases the loss of vital soil moisture needed for plant growth, greatly raising the risk of erosion and land degradation [74]. Understanding the complex relationship between climate and the deposition of silt and other sediments is key for developing sustainable strategies for managing land and water resources, especially amid the accelerating climate change the world faces [68].

Figure 8 shows the spatial distribution of temperatures in the Choman, Mergasur, Rawanduz, Shaqlawa, and Soran regions, divided into five main categories: very low (below 35°C), low (35–40°C), medium (40–45°C), high (45–50°C), and very high (above 50°C). The choman region has the lowest average surface temperatures, with about 39.8% of its area in the low category, 24.6% in the medium, and only 6.1% in the very high category. Mergasur features higher proportions of low (around 36.3%) and medium (around 27.7%) temperatures, along with areas with high (around 22.8%) and very high (around 12.1%) temperatures, indicating greater temperature variation within the region. Rawanduz shows a more balanced distribution among low (roughly 30.8%), medium (roughly 32.6%), and high (roughly 28.3%) categories, suggesting more moderate and stable thermal conditions. Shaqlawa is the hottest and driest area in the study, with most of its land in the very high temperature category (about 49.6%), reflecting significant thermal stress and environmental fragility. Soran exhibits a great diversity in temperature patterns, with ranges from moderate (about 23.9%), low (about 28.2%), to high (about 23.9%), indicating varied thermal environments within the same region.

3.10. NDVI

Figures 8 and 9 offer a detailed view of vegetation distribution in the study area during July and August 2024. This depiction is based on the (NDVI), a reliable tool for evaluating vegetation health and status. In these figure, forested regions are distinctly marked in green, while non-forested areas are shown in white, making it easy to visually distinguish the two main land types. This detailed analysis of vegetation reveals considerable variations and prominent differences among the various districts in terms of vegetation health and dominant land cover patterns. These differences stem from multiple factors, including climate, soil type, agricultural activities, and environmental management.

Figure 10 presents a direct, quantitative comparison of the proportion of forested and non-forested land in five specific districts, offering insights into each area's environmental condition. These districts include: Choman, which has the lowest forest cover at only 25.9%; Mergasur, which boasts the highest forest cover at 67.4%; Rawanduz, which shows a relatively balanced ratio with a forested area of 55.7%; Shaqlawa, with the smallest forested area at only 22.1%; and Soran, with a forested area of 41.4%.The varying percentages reflect the current vegetation cover state in each region and significantly influence the stability of the regional ecosystem, as well as local temperature patterns. Areas with higher non-forested land proportions, such as Shaqlawa and Shuman, are notably linked to rising surface temperatures. This strong correlation highlights the direct relationship between reduced vegetation cover and temperature increases, emphasizing the urgent need for restoring lost vegetation through targeted and efficient agricultural strategies.

Conversely, regions with more extensive forested areas, like Mergasur and Rawanduz, feature healthier, more vibrant vegetation and notably lower surface temperatures. This underscores the positive effects and numerous benefits of vegetation cover on overall environmental health and local climate regulation, stressing the importance of preserving and managing forests sustainably. Soran serves as a transitional zone between these two states, where targeted and controlled agricultural practices can significantly improve local environmental health and reduce environmental pressures. Through sustainable and proper agricultural methods, Soran's vegetation condition can be enhanced, contributing to better overall environmental quality.

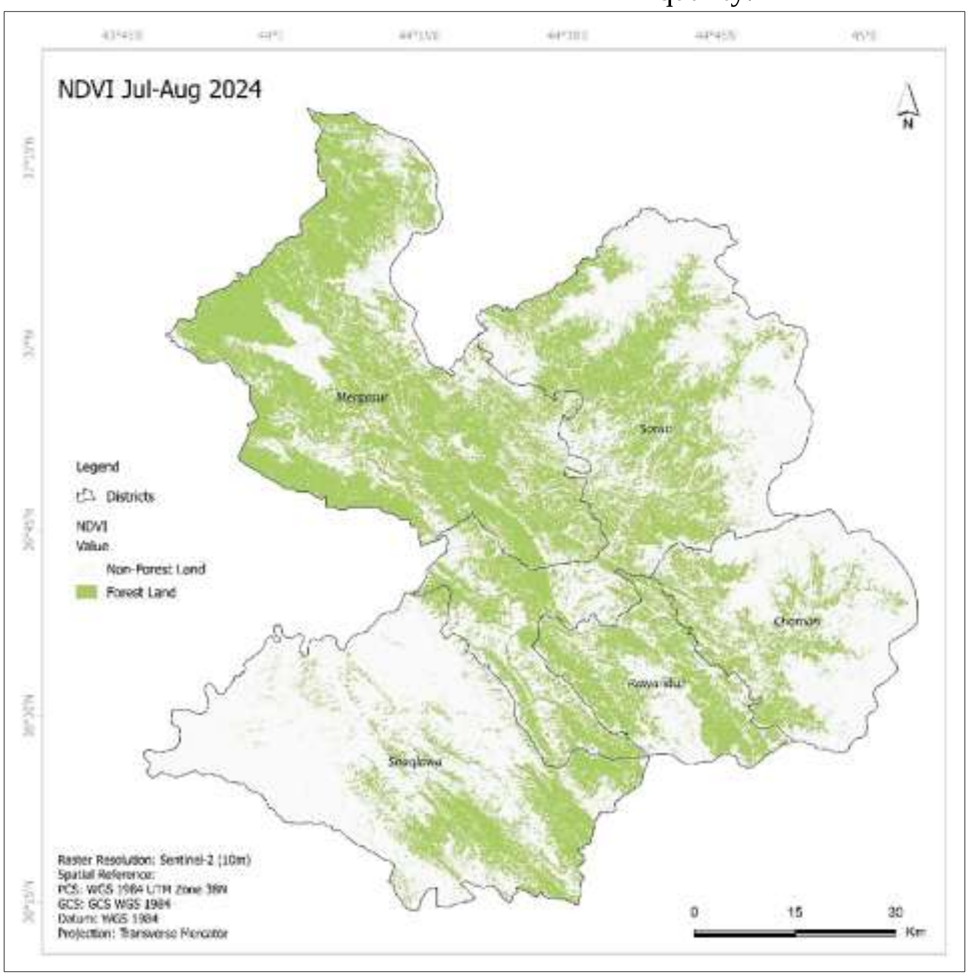

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Figure 8: The Spatio-Temporal pattern of NDVI of the research site.

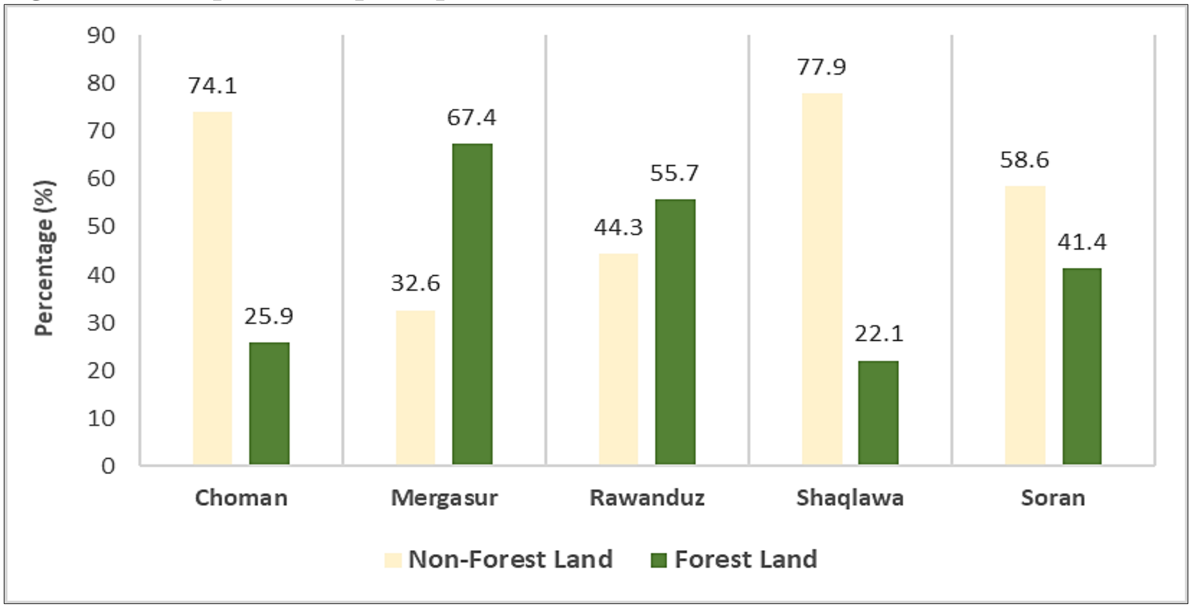

Figure 9: The Spatio-Temporal pattern of NDVI of the research site.

In forestry and ecological studies, a higher NDVI often indicates healthier vegetation, suggesting that the local environment (soil moisture regime, microclimate, terrain context, and supporting ecological conditions) is generally favorable for plant growth. Therefore, assigning “very high suitability” to areas with high NDVI (e.g., >0.55) is consistent with identifying places where trees are more likely to establish and survive successfully. In this sense, dense vegetation is not treated as the “target to plant on,” but as an indicator of favorable site conditions.

The reforestation/restoration projects often prioritize degraded or sparsely vegetated areas (low NDVI). Planting in areas with very high NDVI (e.g., ~0.8) may not be necessary if these areas already contain dense vegetation. However, it is important to clarify that our suitability mapping is a district-scale planning tool and does not imply that planting will be conducted on the exact same high-NDVI pixels. Operational implementation typically selects appropriate planting parcels within the broader suitable zones, while excluding already forested/densely vegetated patches based on field validation and land-use constraints.

3.11. Slop

Figure 10 displays the distribution of slopes in the study area, offering a precise classification of inclines from least to steepest. The classification begins with moderate slopes of 0-3.43 degrees (light green) and progresses to steep slopes of 45 degrees. The map clearly shows significant topographical differences across the study area. For instance, the Choman and Saran districts, along with parts of Rawanduz, feature steep slopes ranging from orange to dark red, indicating slopes of 21.8 degrees and higher. This suggests rugged, challenging terrain. Conversely, the Shaqlawa and Mergasur districts have a mix of moderate and medium slopes, shown in green and yellow, reflecting more gentle terrain. Nonetheless, a few areas in Shaqlawa and Mergasur also have steep slopes, contributing to the area's topographical diversity. This wide variation in slope greatly influences land

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suitability for various agricultural uses. Steep slopes hinder the development of vegetation, complicate soil conservation efforts, and make water resource management difficult. These issues are due to increased erosion risk, soil instability, and the challenges of accessing these areas for farming. Therefore, it is crucial to adopt specialized strategies, such as planting dense vegetation to stabilize soil and reduce erosion caused by rain and wind.

In contrast, the moderate slopes in Shaqlawa and Mergasur create more favorable conditions for growing diverse vegetation and supporting successful afforestation projects. These slopes allow for better land management and improve soil water retention, which lessens erosion risk and enhances soil quality. As a result, these areas are better suited for sustainable environmental restoration and agricultural development. Previous analyses of the (NDVI), which measures vegetation density, along with lowland measurements, have shown that slope conditions greatly influence the success of afforestation. Areas with steep slopes like Choman and Soran require careful environmental management, including techniques like terrace planting helping to level the land and contour planting which follows contour lines to reduce erosion. These methods aim to stabilize rugged terrain, boost vegetation cover, and lessen environmental risks associated with steep slopes. The model indicates a clear decline in forest cover, reflecting a decrease in forested areas. This trend aligns with rising temperatures and increased drought, highlighting how climate change impacts vegetation and the environment as a whole. These conditions highlight the urgent need to protect existing forests and promote reforestation to mitigate the effects of climate change and preserve biodiversity.

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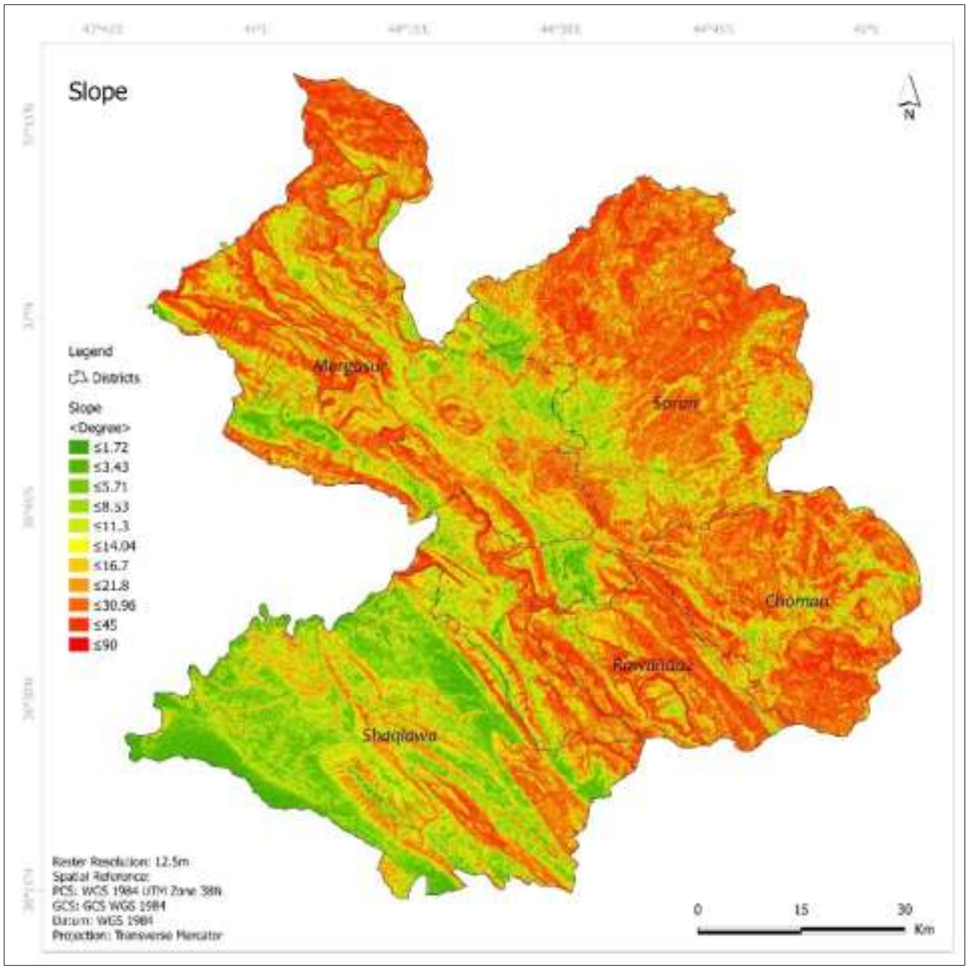

Figure 10: Map depicting the Slope of the research site.

The purpose of using aspect is to find the areas in which the temperature changes very little and is more static [75]. In terms of slopes, as they decrease, the risk of erosion damage also decreases. Optimal slopes should range between 0 and 10% [76, 77]. For land cover, large barren lands are the main targets for planting [13]. The strength of the slope, coupled with the narrow confidence interval, instills a high degree of confidence in the stability of this estimate[78]. The presence of water increases the possibility of reforestation success, and the quality of the land also increases [79, 80].

3.12. Statically Analyses

3.12.1. Shaqlawa Districts

Figure 10 shows a principal component analysis (PCA) diagram, which visually summarizes the complex relationships among environmental variables. While this diagram displays the distribution of these variables, Table A1 presents the Pearson correlation matrix. This statistical tool provides a quantitative measure of the strength and direction of linear correlations between the environmental parameters. The studied parameters include the natural vegetation cover index (NDVI), an indicator of vegetation density and health; rainfall, a key factor affecting soil moisture and plant growth; land surface temperature (LST), reflecting the thermal energy released from the land surface; the digital elevation model (DEM), indicating land surface elevation.

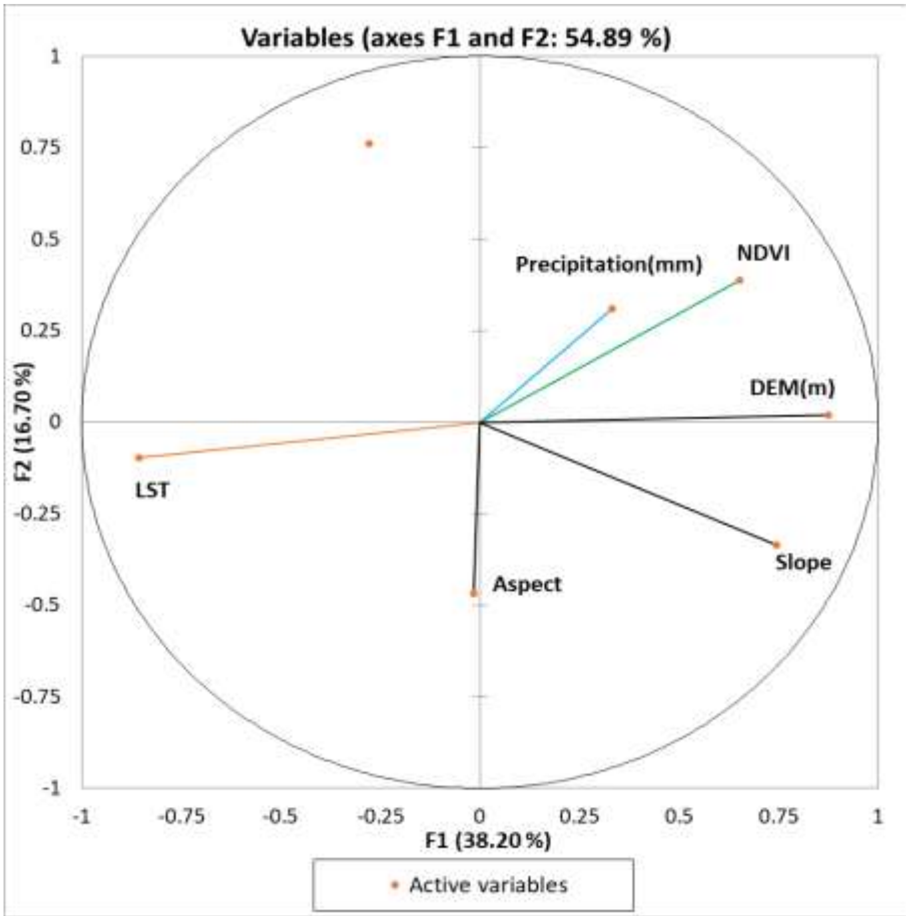

Figure 10: PCA Biplot of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Shaqlawa District.

The PCA diagram indicates that the first two factors (F1 and F2) together explain 54.89% of the data's variance, showing these two factors capture a significant portion of the information in the environmental variables. F1 accounts for 38.20%, while F2 explains 16.70%. Variables such as NDVI, DEM, slope, and rainfall cluster positively along the F1 axis, suggesting a positive correlation among them. This grouping implies that higher elevations (DEM) are associated with increased rainfall, which correlates with higher vegetation density (NDVI). In other words, higher elevations tend to have more favorable conditions for rainfall and thus support vegetation growth. Conversely, LST and slope are negatively correlated along F1, implying that higher temperatures may adversely affect vegetation health and rainfall patterns. Elevated temperatures could stress vegetation, leading to lower density, and similarly negatively influence rainfall. The correlation matrix (Table A1) supports these PCA findings, showing a significant negative correlation between NDVI and LST (-0.505), indicating that higher surface temperatures tend to decrease vegetation health

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and density. This aligns with findings by Zhang, Yin [81], who reported a similar negative relationship between LST and NDVI. Additionally, DEM shows a strong positive correlation with NDVI (0.473), reinforcing the idea that higher elevations support greater vegetation productivity due to favorable climatic conditions. Furthermore, DEM is significantly negatively correlated with LST (-0.739), confirming the well-known pattern of decreasing temperature with increasing altitude, consistent with the atmospheric lapse rate outlined by Li, Hou [15], The negative correlation between slope and LST (-0.500) suggests that steeper slopes may experience reduced sunlight exposure or improved drainage, resulting in lower surface temperatures. The moderate positive correlation between slope and NDVI (0.262) indicates that gentler slopes likely support better vegetation growth by reducing waterlogging and soil erosion. Slope direction showed weak correlations with most variables, implying its limited impact on the studied environmental parameters. The two main axes (F1: 29.14%, F2: 18.26%) explain 47.40% of the variance. Analysis of the variable positions reveals clear relationships, with LST being negatively correlated with DEM and regression. This is supported by the correlation matrix, which shows a significant negative correlation between LST and DEM (-0.761), confirming a strong inverse relationship between land surface temperature and elevation, consistent with the findings of Liu et al. (2021).

3.12.2. Soran Districts

Figure 11 and Table A2 present the negative correlation between LST and slope (-0.268), which reinforces this finding, suggesting cooler temperatures on steeper terrains, potentially due to reduced direct solar radiation or improved water drainage conditions [82]. NDVI is negatively correlated with LST (-0.240), indicating that higher surface temperatures negatively impact vegetation health. This aligns with existing research, confirming that increased surface temperature adversely affects vegetation vigor, as higher temperatures may stress vegetation, reducing greenness [83]. Precipitation exhibits weak correlations with all variables, suggesting minimal direct influence within this dataset. However, minor positive correlations exist with slope (0.072) and aspect (0.076), possibly hinting at subtle topographic influences on localized rainfall distribution patterns, consistent with the findings of Barry [84]. regarding microclimatic variations due to terrain. Aspect exhibits weak correlations overall, suggesting the limited significance of directional exposure on environmental factors measured within this context.

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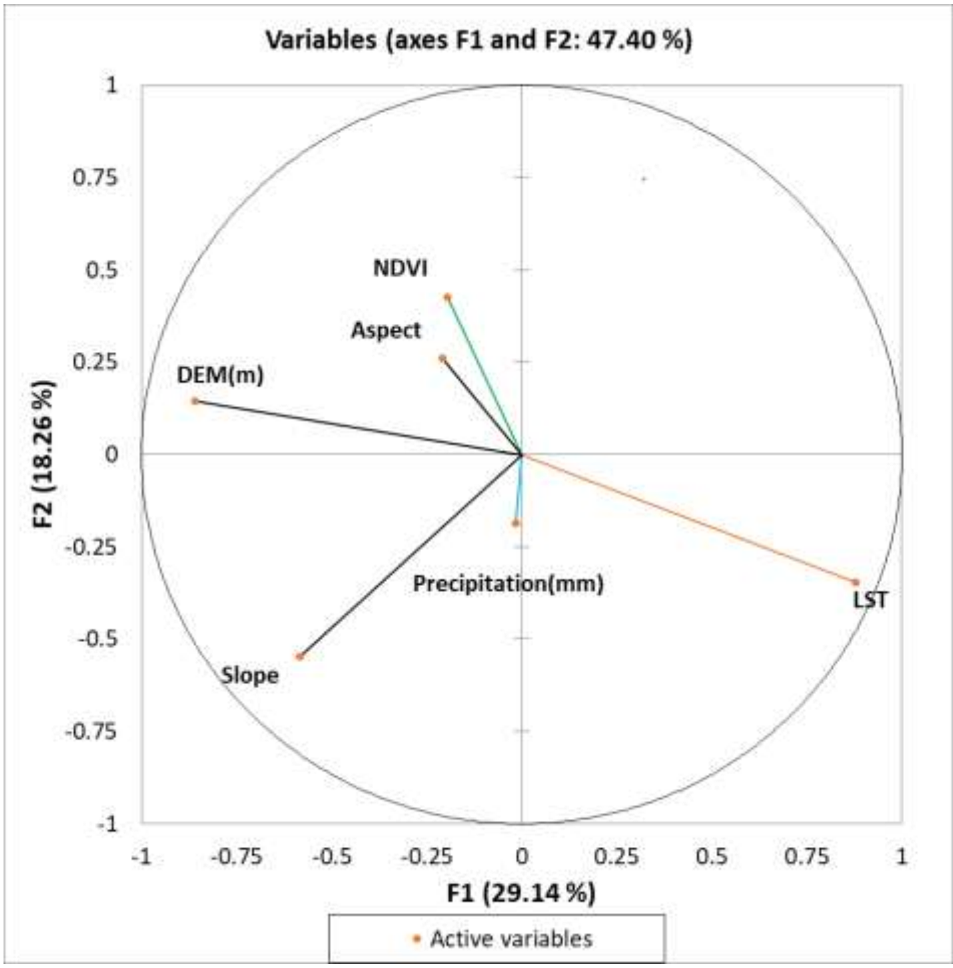

Figure 11: PCA Biplot of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Soran District.

3.12.3. Rawanduz Districts

Table A3 and Figure 12, the PCA correlation circle Table A3 and Figure 12 illustrate the principal component analysis (PCA) results for the Rawanduz region, where two main axes account for 46.74% of the variance (F1: 26.60%, F2: 20.14%). The correlation matrix reveals a significant negative correlation between the digital elevation index (DEM) and the sea surface temperature index (LST) (-0.681), indicating a strong inverse relationship between elevation and temperature, supported by the elevational temperature gradient [85].The natural vegetation cover index (NDVI) is also negatively correlated with LST (-0.218), showing that higher surface temperatures negatively impact vegetation health, consistent with research on vegetation stress under increasing thermal conditions [81]. Additionally, there is a weak negative correlation between NDVI and directional exposure (-0.129), suggesting limited effect of exposure on vegetation health [86]. Rainfall is modestly positively correlated with DEM (0.181), indicating a slight increase in rainfall at higher elevations [84]. while slope and rainfall are negatively correlated (-0.129). The

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PCA results reinforce these relationships, with vectors for DEM and LST pointing in opposite directions, reflecting a strong negative correlation between elevation and temperature, and slope showing a weaker positive correlation with DEM.

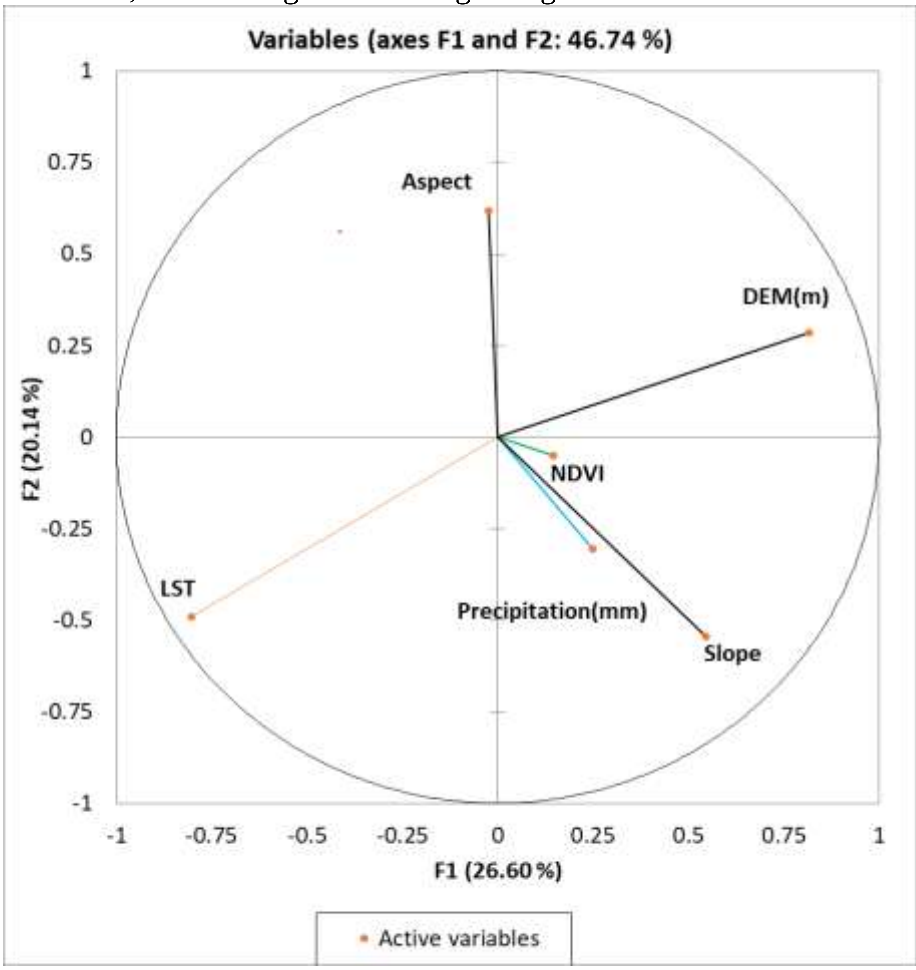

Figure 12: PCA Biplot of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Rawanduz District

3.12.4. Choman Districts

Table A4 and the principal component analysis (PCA) correlation in Figure 13 for the Choman counties illustrate the relationships among the Natural Vegetation Index (NDVI), rainfall, sea surface slope (LST), digital elevation model (DEM), slope, and laterality. PCA accounts for 51.43% of the variance across two axes (F1: 32.59%, F2: 18.84%). Both DEM and LST exhibit a strong negative correlation (-0.746), indicating a significant decrease in land surface temperature with increasing elevation, supporting the well-known elevation temperature gradient (Liu et al., 2021). The digital elevation model correlates positively with rainfall (0.454), suggesting higher rainfall at elevated areas, aligning with Barry [84], who describes mountains usually receiving more precipitation. The NDVI correlates moderately negatively with DEM (-0.298) and slope (-0.241), implying vegetation limitations at higher elevations or steeper slopes, possibly due to harsh climate conditions and less stable

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soils [87]. The TWI shows a strong negative correlation with slope (-0.351), indicating steeper slopes tend to have less water accumulation, consistent with known hydrological principles [86]. Laterality correlates slightly negatively with LST (-0.200), suggesting a possible influence of slope side on local temperature, though weak. The PCA correlation circle visually supports these relationships, especially the strong inverse correlation between DEM and LST, emphasizing their inverse relationship. Additionally, rainfall vectors and DEM are positively correlated.

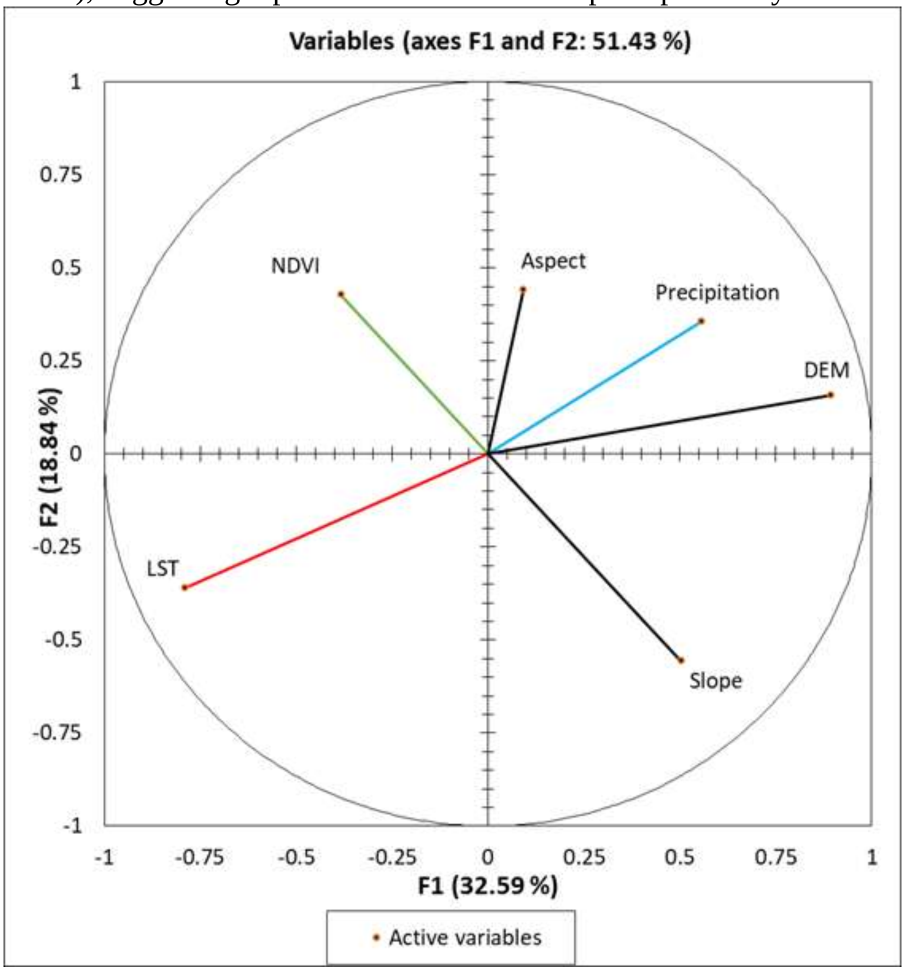

Figure 13: PCA Biplot of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Choman District

3.12.5. Mergasur Districts

This section presents the results of analyzing environmental variables in the Mergasur region, focusing on the relationships among the Normalized Difference Vegetation Index (NDVI), rainfall, ground surface temperature (LST), digital elevation model (DEM), slope, and laterality. Principal component analysis (PCA) explains 47.51% of the variance with two principal components (F1: 30.19%, F2: 17.31%). Table A5 and Figure 14 illustrate these relationships. The correlation matrix (Table A5) shows several statistically significant negative correlations. Notably, a strong inverse relationship exists between

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NDVI and ground surface temperature (-0.424), indicating that higher surface temperatures negatively impact vegetation health, consistent with Zhang, Xiao [83], The relationship between the digital elevation model (DEM) and the low elevation model (LST) is highly negative (-0.584), supporting the well-known fact that higher elevations tend to have lower temperatures, as documented in mountain climate research [85]. Additionally, slope is negatively correlated with LST (-0.364), suggesting that steeper terrain generally has less water accumulation and cooler surface temperatures, in line with hydrological and climatological studies by Zarei and Shabani [82], Conversely, the elevation model shows weak correlations with most other variables, implying that directional exposure has a limited effect on environmental dynamics in this region. The PCA pie chart (Figure 14) visually confirms these key relationships. It particularly highlights the opposing trends of the LST and DEM vectors, emphasizing their inverse relationship.

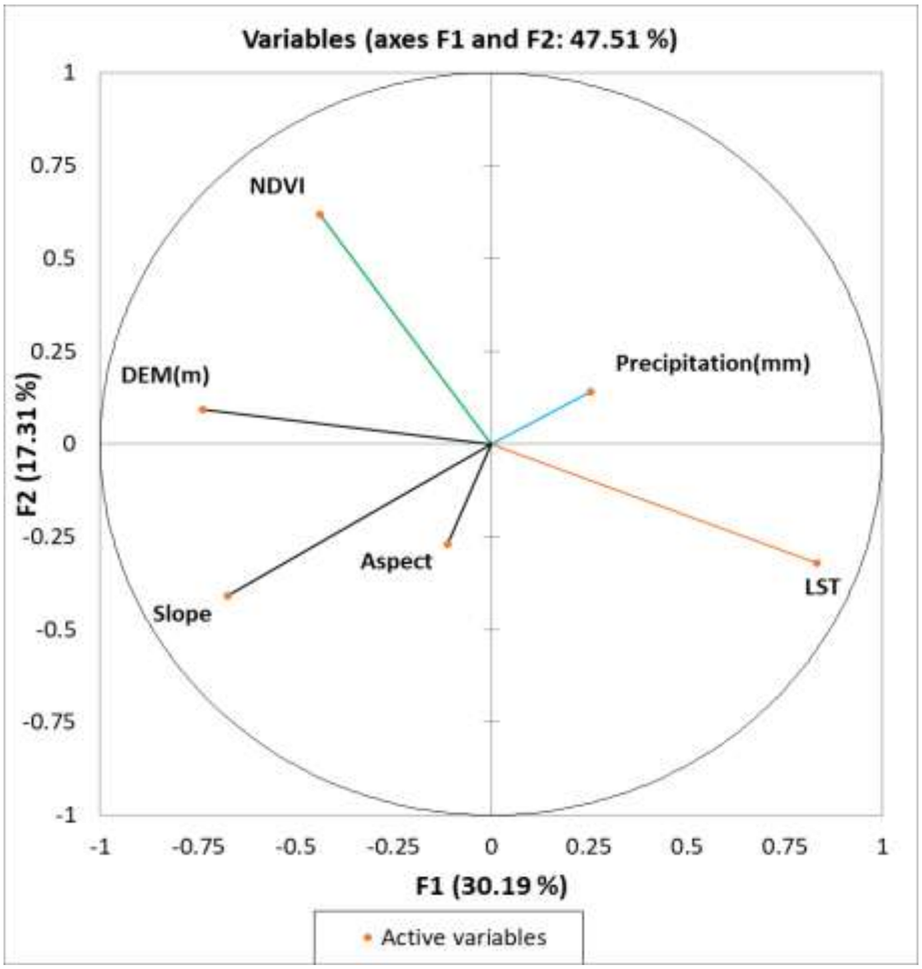

Figure 14: PCA Biplot of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Mergasur District.

3.13. Regional suitability distribution.

In the five areas (totaling approximately 7,289 square kilometers), the middle and lower

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classes dominate the restoration suitability. Moderate suitability accounts for the largest share (29.3%, or approximately 2,138 square kilometers), followed closely by low suitability (27.5%, or approximately 2,006 square kilometers) and very low suitability (18.1%, or approximately 1,322 square kilometers). Areas with high and very high suitability together constitute approximately 25.0% (approximately 1,823 square kilometers), while very high suitability alone covers 7.0% (approximately 512 square kilometers) (Table 1; Figures 15 and 16). This overall distribution highlights the landscape's considerable potential for restoration when combined with site preparation, but it suggests that only a relatively small portion is suitable for immediate, large-scale cultivation without further treatment [65, 88]. However, there are marked differences between the regions. Mergasur enjoys the best conditions, with 58.7% of its area classified as high (35.9%) or very high (22.8%), thereby constituting the majority of the region's highest-class hectares (Tables 1 and 2). In stark contrast, the choman region is dominated by very low (40.0%) and low (35.1%) areas, with only 5.5% considered high or very high, reflecting the prevalence of steep terrain and cold, high-altitude conditions that severely limit agricultural potential. Shaqlawa and Soran exhibit more varied, though generally moderate, suitability patterns. Shaqlawa is dominated by low (34.4%) and medium (39.4%) areas, with 12.6% in the higher categories, while Soran shows a similar pattern with low (32.3%), medium (31.2%), and 16.9% in the high/very high categories. Rawanduz is relatively more restricted, with only 5.0% classified as high or very high, which is consistent with its rugged terrain [89]. The spatial distribution of suitability categories strongly aligns with the biophysical factors typical of semi-arid mountainous regions. High- and very-high-suitability patches are consistently found in the medium-elevation areas (approximately 300–800 m²) with gentle slopes (approximately 15%), cooler surface temperatures, and favorable north- and east-facing sides. Conversely, very low-suitability groups cluster on steep hillsides and hot, exposed lowlands (Figures 15 and 16; Tables 1 and 2).

Table 1. Suitability class areas and percentages by district

	Land Cover Suitability Class		**Very low 1**	**Low 2**	**Medium 3**	**High 4**	**Very high 5**	**Total**
Districts	**Choman**	Count	395254.0	346963.0	186295.0	56838.0	2979.0	
		Area_km^2	355.7	312.3	167.7	51.2	2.7	**889.5**
		%	40.0	35.1	18.8	5.8	0.3	**100.0**
	Mergasur	Count	141425.0	227103.0	537703.0	786859.0	500494.0	
		Area_km^2	127.3	204.4	483.9	708.2	450.4	**1974.2**
		%	6.4	10.4	24.5	35.9	22.8	**100.0**
	Rawanduz	Count	206693.0	213076.0	137655.0	28347.0	1124.0	
		Area_km^2	186.0	191.8	123.9	25.5	1.0	**528.2**
		%	35.2	36.3	23.5	4.8	0.2	**100.0**
	Shaqlawa	Count	265738.0	676961.0	774742.0	234869.0	13548.0	
		Area_km^2	239.2	609.3	697.3	211.4	12.2	**1769.3**
		%	13.5	34.4	39.4	11.9	0.7	**100**
	Soran	Count	459733.0	764436.0	739312.0	350690.0	50241.0	
		Area_km^2	413.8	688.0	665.4	315.6	45.2	**2128.0**

	%	19.4	32.3	31.3	14.8	2.1	**100.0**
	Count	1468843.0	2228539.0	2375707.0	1457603.0	568386.0	
All Districts (sum)	Area_km^2	1322.0	2005.7	2138.1	1311.8	511.5	**7289.2**
	%	18.1	27.5	29.3	18.0	7.0	**100.0**

A multi-criteria assessment based on soil analysis (AHP), which weighted factors such as rainfall, slope, natural vegetation index (NDVI), elevation, laterality, and ground surface temperature (LST) [90], prioritized water availability, topographic stability, and humid local climates, which are more predictive of seedling survival [91]. The dominance of Mergasur in the upper layers is consistent with this logic: the middle layers with more moderate slopes reduce erosion and improve infiltration, while cooler surfaces reduce evaporative demand. Conversely, the prevalence of lower strata in Choman and Rawanduz is due to steep gradients (>25–35%) and exposure, which significantly increases the risk of erosion and establishment costs [92]. From a management perspective, the findings support a two-pronged strategy.

Table 2. Reclassification thresholds for NDVI, precipitation, slope, elevation, aspect, LST (class 1–5 from very low to very high).

Factor (Raster) / weights	Min–Max values	Class 1 (Very Low Suitability)	Class 2 (Low)	Class 3 (Moderate)	Class 4 (High)	Class 5 (Very High Suitability)	Reason & Notes
NDVI / %20	-0.427 → 0.829	< 0.1	0.1 – 0.25	0.25 – 0.4	0.4 – 0.55	> 0.55	Higher NDVI indicates greener vegetation and is better for reforestation.
Precipitation (mm) / %20	446 → 1397	< 500 mm	500 – 700 mm	700 – 900 mm	900 – 1100 mm	> 1100 mm	More rainfall = higher suitability.
Slope (%) / 10	-0.43 → 83.89	> 35%	25 – 35%	15 – 25%	5 – 15%	0 – 5%	Gentle slopes preferred (5–15%).
DEM (m) /	288 →	> 2000 m	1500 –	1000 –	500 –	300 – 500	Mid-elevations

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%20	3619		2000 m	1500 m	1000 m	m	are optimal for trees.
Aspect (°) / %10	0 → 360	South (135°–225°)	SE/SW (105°–135°, 225°–255°)	East/West (75°–105°, 255°–285°)	NE/NW (45°–75°, 285°–315°)	North (315°–45°)	North aspects are better in dry climates.
LST (°C) / %20	8.26 → 68.00	> 50°C	40 – 50°C	30 – 40°C	20 – 30°C	< 20°C	Lower land surface temperature is better for tree growth.

The first is to maximize efficiency by immediately expanding cultivation in the highly suitable areas of Mergasur. The second involves treating the low- and intermediate-salinity landscapes of Soran and Shaqlawa as reclamation projects, integrating agriculture with site-level interventions. These interventions could include micro watersheds, vegetation cover, paving/building on slopes ranging from 5 to 15%, and restricted grazing areas to improve conditions toward higher suitability [93]. In the most rugged regions of Choman and Rawanduz, efforts should be narrowly focused on river corridors, valley bottoms, and north- and east-facing slopes, prioritizing supported natural regeneration where total agriculture is impractical. [94]. One key modeling decision to note is how NDVI is handled. The current approach favors greener sites, which makes sense for maximizing short-term planting success. However, if the goal is to rehabilitate degraded land, a complementary "Scenario-B" should reduce or reverse the NDVI impact, prioritizing areas with low NDVI for intervention.

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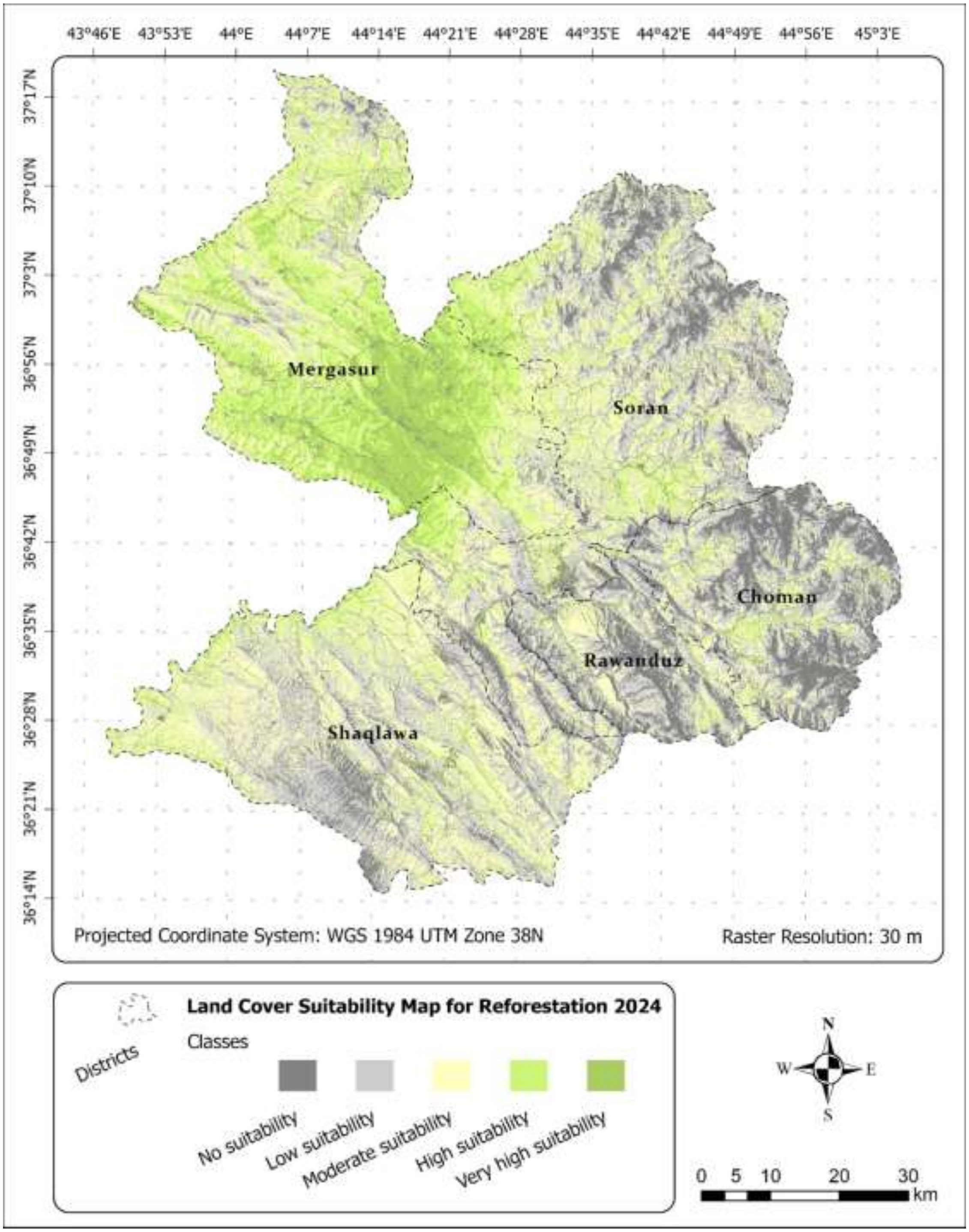

Figure 15. District-wide suitability map.

By reporting both scenarios, we can increase transparency and help align recommendations with different stakeholder goals [88, 94]. We face uncertainties from input data (e.g., NDVI, rainfall, DEM-derived slope), temporal variability (using a single NDVI/LST date), and threshold selection. To address this, we recommend sensitivity tests on weights (±5–10% for top criteria), multi-year NDVI/LST composites to reduce seasonal noise, and

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targeted field validation, especially along class boundaries and in outliers, to refine criteria and confirm feasibility. Additionally, incorporating soils, land tenure, and pressure layers (such as roads, settlements, and grazing) in a follow-up screening would further refine operational priorities [95, 96]. The model distinguishes between contrasting conditions, such as Shaqlawa urban hotspots (where higher LST and urban effects reduce suitability despite moderate rainfall) and the Mergasur wetland/high-moisture zones (where higher rainfall and moisture-related conditions increase suitability). This explanation is now linked to the weighted MCDA structure (rainfall as a key criterion combined with LST and other terrain factors), demonstrating how spatial variability in precipitation and temperature is reflected in different suitability outcomes across the study area.

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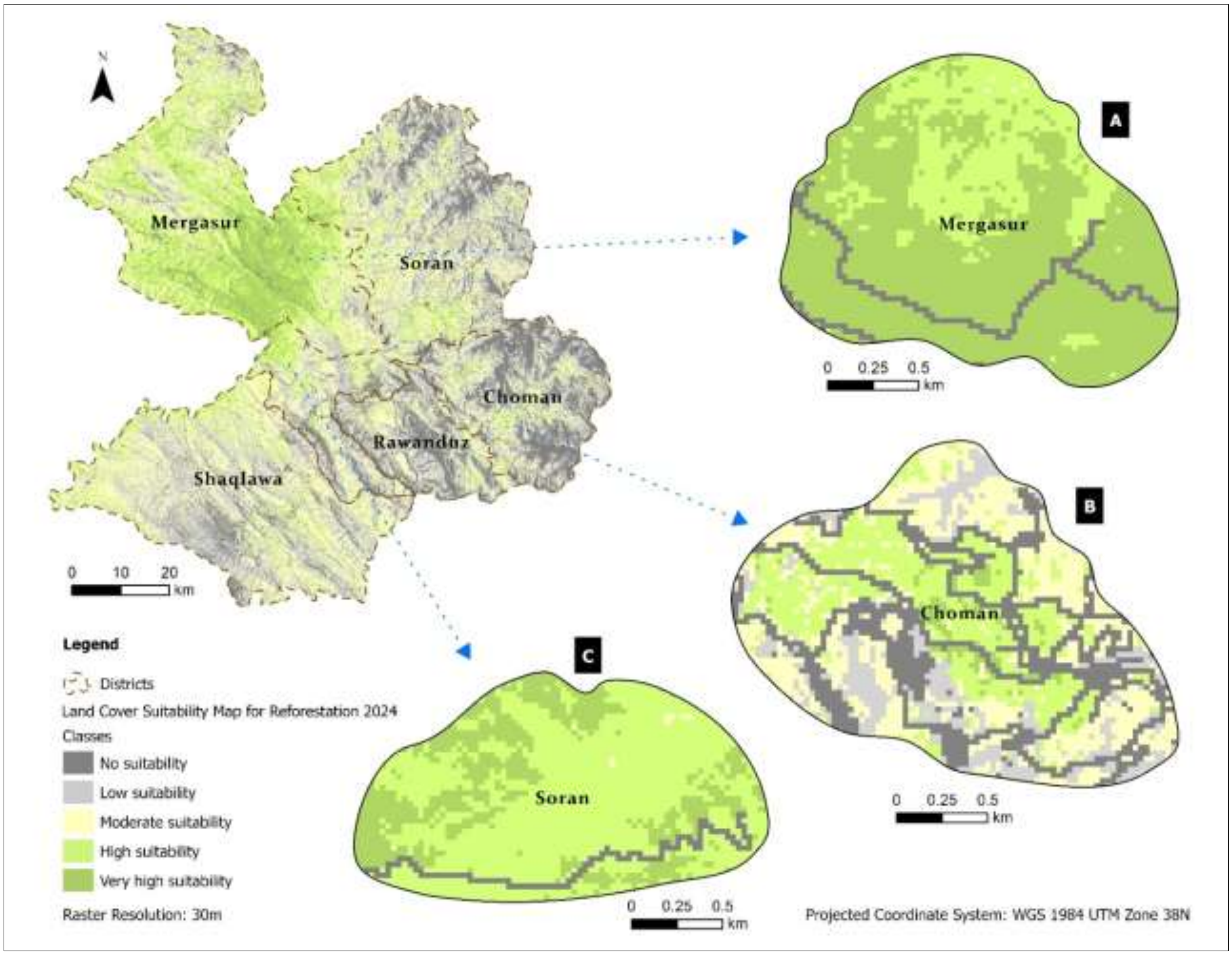

Figure 16. Land-cover suitability for reforestation with district insets (A: Mergasur, B: Choman, C: Soran).

4. Discussion

The Current research consistently emphasizes the vital role of Geographic Information Systems (GIS) and Remote Sensing (RS) in pinpointing ideal reforestation locations. These advanced tools provide reliable, efficient, and scientifically based methods by integrating complex environmental, social, economic, and ecological factors [97]. Additionally, GIS and RS are crucial in watershed management, combining morphometric, land-use, and soil data to develop thorough conservation strategies. The use of satellite imagery to produce thematic maps highlights its significant potential for environmental management and sustainable land-use planning.

Recent studies showcase the power of combining multi-criteria analysis with spatial data. For instance, Casisirano, Mendoza [98]. merged Analytical Hierarchy Process (AHP) with remote sensing data to identify priority zones for tree planting in urban areas of the Philippines. They incorporated expert opinions and factors such as air quality, tree cover, and urban heat islands (UHIs) into detailed spatial maps, creating an agriculture priority index that effectively guides urban reforestation initiatives. Building on this, Kordrostami, Attarod [99] used the Fuzzy Analytical Network Process (FANP) within a multi-criteria framework, allowing for detailed decision-making in complex settings. Their method successfully identified key sub-basins in semi-arid regions for reforestation, prioritizing environmental factors like morphological measurements and topography, which is especially useful where ground data is limited. Other research demonstrates straightforward yet effective spatial analysis techniques Mahdavi, Ghasemi [100]. applied logical methods within a geographic information system (GIS) to locate suitable habitats for native trees, showing how simple spatial analysis can effectively support reforestation focused on ecological compatibility and local adaptability. Further emphasizing this approach's value in forestry, Faisal, Asghar [101] ,similar to Faisal et al. (2024), in Turkey, employed satellite imagery to accurately evaluate afforestation potential, reinforcing the significance of remote sensing as a key forestry tool. This was demonstrated by identifying critical native tree habitats using soil and environmental data within GIS through Boolean logic.

Moreover, thermal infrared remote sensing is vital in assessing land surface temperature (LST) and urban heat islands (UHIs) (Weng, 2009). This is essential for selecting reforestation sites that can help mitigate extreme climate variability and improve urban environmental resilience. Zhou, Zhao [102]. emphasized the importance of understanding the spatial variation and vegetation conditions of urban heat islands to better target urban reforestation using thermal and vegetation data. Additionally, integrating hydrological models, such as the physically-based variable contributing area model [86], aids in analyzing surface runoff and soil moisture, two key factors for site suitability. Combining topographic variables with satellite-derived vegetation indices, especially in mountainous areas, highlights the importance of topographically based hydrological assessments in reforestation planning [103].

GIS and remote sensing (RS) offer multi-layered analytical capabilities that greatly enhance the process of identifying the best reforestation sites. Recent advances, like improving RTK positioning with numerical weather prediction models [104], enable highly precise geolocation, which is crucial for site selection and monitoring. Overall, these studies underscore the significant advantages of integrating GIS, RSS, multi-criteria analysis, and advanced statistical methods to boost reforestation success. These combined approaches offer practical, evidence-based insights for policymakers and environmental scientists, significantly improving environmental sustainability and climate

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resilience through more accurate and efficient site selection.

5. Conclusion

This study uses spatial and temporal analyses of key environmental parameters, rainfall, elevation, surface temperature, vegetation index, and slope, to guide targeted afforestation planning in Erbil Governorate. The assessment reveals significant spatial differences in environmental conditions, providing a strong basis for developing site-specific management strategies. Rainfall varies considerably across the region, with Mergasur recording the highest levels, making it ideal for afforestation. In contrast, areas like Shaqlawa face challenges due to low rainfall. Topographic slope analysis shows that north- and east-facing slopes (notably in Mergasur and Soran) benefit from favorable local climates, while south- and west-facing slopes (particularly in Shaqlawa and Harir) require drought-tolerant species and specialized water management. Digital elevation models highlight differences in suitability zones: higher-altitude areas (such as Choman and Soran) need cold-tolerant species and erosion control measures, whereas lower-altitude zones (such as Shaqlawa) favor drought-tolerant varieties. LST analysis indicates environmental stress in Shaqlawa and Mergasur due to high temperatures linked to limited vegetation cover and potential land degradation. In contrast, Choman exhibits cooler conditions, showing healthier vegetation and greater environmental resilience. Analysis of the NDVI confirms a strong relationship between plant health and LST, emphasizing environmental vulnerability in regions like Shaqlawa and Choman, where sparse vegetation is common. Conversely, areas such as Mergasur and Rawanduz show healthier vegetation linked to lower temperatures and better resilience. Slope analysis reveals significant challenges for plant growth on the steep terrain of Choman, Soran, and Rawanduz, which may require techniques like terrace farming and contour planting. Areas with medium to low slopes (such as Shaqlawa and Mergasur) offer more favourable conditions for sustainable development and restoration.

Statistical methods, including PCA and correlation matrices, confirm an inverse relationship between the vegetation index and LST, with elevation being the primary factor influencing local temperature regimes and plant health. Based on these findings, a set of strategic recommendations are proposed to improve the success of afforestation efforts:

1- Prioritize site and water management: In Mergasur, focus on afforestation using specialized approaches, such as irrigation and drought-resistant species, in low-rainfall areas like Shaqlawa and Harir.

2- Implement soil stabilization: Use terraces and contour planting on steep slopes in areas such as Choman, Soran, and Rawanduz to reduce erosion and improve tree survival.

3- Match species to altitude: Select cold-tolerant species for high elevations (Shuman and Soran) and drought- and heat-tolerant species for lower elevations (Shaqlawa and Rawanduz).

4- Adapt to local climate: Choose species based on terrain of the slopes, with shade-tolerant species for north/east slopes and drought-tolerant species for south/west slopes.

5- Manage heat stress: Carry out strategic urban afforestation and planting in warmer areas (Shaqlawa and Mergasur) to lower groundwater rise and strengthen environmental resilience.

6- Focus on environmental conservation: In ecologically stable, cold, and vegetated areas, like Shuman's, prioritize protecting existing ecosystems over large-scale new agriculture.

7- Ensure ongoing monitoring: Use remote sensing and GIS for continuous environmental

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assessment to observe changes and adapt management strategies as needed.strategies.

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Potential conflicts of interest. The authors declare no conflict of interest.

Appendix

Table A1. Pearson Correlation Matrix of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Shaqlawa District.

Correlation matrix :

Variables	NDVI	Precipitation(mm)	LST	DEM(m)	Slope	Aspect
NDVI	**1**	**0.168**	**-0.505**	**0.473**	**0.262**	**-0.058**
Precipitation(mm)	**0.168**	**1**	**-0.190**	**0.171**	**0.173**	**-0.086**
LST	**-0.505**	**-0.190**	**1**	**-0.739**	**-0.500**	-0.045
DEM(m)	**0.473**	**0.171**	**-0.739**	**1**	**0.564**	-0.015
Slope	**0.262**	**0.173**	**-0.500**	**0.564**	**1**	0.006
Aspect	**-0.058**	**-0.086**	-0.045	-0.015	0.006	**1**

Values in bold are different from 0 with a significance level alpha=0.05

Table A2. Pearson Correlation Matrix of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Soran District.

Correlation matrix						
Variables	NDVI	Precipitation (mm)	LST	DEM(m)	Slope	Aspect
NDVI	**1**	0.030	**-0.240**	0.012	0.011	-0.020
Precipitation(mm)	0.030	**1**	**0.064**	-0.001	**0.072**	**0.076**
LST	**-0.240**	**0.064**	**1**	**-0.761**	**-0.268**	**-0.206**
DEM(m)	0.012	-0.001	**-0.761**	**1**	**0.295**	**0.061**
Slope	0.011	**0.072**	**-0.268**	**0.295**	**1**	-0.018
Aspect	-0.020	**0.076**	**-0.206**	**0.061**	-0.018	**1**

Values in bold are different from 0 with a significance level alpha=0.05

Table A3. Pearson Correlation Matrix of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Rawanduz District

Correlation matrix :							
Variables	NDVI	Precipitation(mm)	LST	DEM(m)	TWI	Slope	Aspect
NDVI	**1**	0.026	**-0.218**	-0.097	0.053	0.077	**-0.129**
Precipitation(mm)	0.026	**1**	0.021	**0.181**	-0.055	0.099	**-0.129**
LST	**-0.218**	0.021	**1**	**-0.681**	0.039	**-0.179**	**-0.211**
DEM(m)	-0.097	**0.181**	**-0.681**	**1**	**-0.113**	**0.144**	-0.040
TWI	0.053	-0.055	0.039	**-0.113**	**1**	**-0.411**	0.070
Slope	0.077	0.099	**-0.179**	**0.144**	**-0.411**	**1**	**-0.140**
Aspect	**-0.129**	**-0.129**	**-0.211**	-0.040	0.070	**-0.140**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

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Table A4. Pearson Correlation Matrix of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Rawanduz District.

Correlation matrix:

Variables	NDVI	Precipitation(mm)	LST	DEM(m)	Slope	Aspect
NDVI	**1**	-0.062	0.041	**-0.298**	**-0.241**	0.045
Precipitation(mm)	-0.062	**1**	**-0.298**	**0.454**	0.041	0.044
LST	0.041	**-0.298**	**1**	**-0.746**	**-0.216**	**-0.200**
DEM(m)	**-0.298**	**0.454**	**-0.746**	**1**	**0.254**	-0.026
Slope	**-0.241**	0.041	**-0.216**	**0.254**	**1**	0.004
Aspect	0.045	0.044	**-0.200**	-0.026	0.004	**1**

Values in bold are different from 0 with a significance level alpha=0.05

Table A5. Pearson Correlation Matrix of NDVI, LST, DEM, Slope, Aspect, and Precipitation in Mergasur District.

Correlation matrix (Pearson):

Variables	NDVI	Precipitation(mm)	LST	DEM(m)	Slope	Aspect
NDVI	**1**	-0.043	**-0.424**	**0.103**	**0.091**	**-0.075**
Precipitation(mm)	-0.043	**1**	**0.072**	**-0.137**	**-0.113**	0.023
LST	**-0.424**	**0.072**	**1**	**-0.584**	**-0.364**	**-0.127**
DEM(m)	**0.103**	**-0.137**	**-0.584**	**1**	**0.306**	-0.004
Slope	**0.091**	**-0.113**	**-0.364**	**0.306**	**1**	**0.069**
Aspect	**-0.075**	0.023	**-0.127**	-0.004	**0.069**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

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