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Research Article

Land Suitability Analysis for Millet across Different Regions of Nepal Using Advanced GIS

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Abstract

Agriculture is the backbone of Nepal's economy. It plays a crucial role in the livelihoods of the majority of the population in Nepal. Millet, including species like *Panicum miliaceum* and *Eleusine corocana*, is especially important due to its ability to thrive in marginal lands and its resilience to drought conditions. This research evaluates the suitability of different region in Nepal for millet cultivation using Geographic Information Systems (GIS). By analyzing soil properties, climate data, topography, land cover etc. this research aims to show the best areas for growing millet. This study also highlights the importance of using land suitability analysis to improve agricultural practices, boost food security and promote sustainable farming. In addition to this, it emphasizes the socio-economic and environmental benefits of millet, including poverty reduction, biodiversity support, and ecological balance.

Keywords: Geographic Information Systems (GIS); Millet; Land; Agriculture; Sustainability

Introduction

Agriculture is the backbone of Nepal's economy. It contributes approximately one-third of the country's GDP and employing about 65% of the population. From the Terai plains to the mid-hills and high mountains, this diverse agro-ecological zones provides a unique environment for cultivation of various crops. Among those crops, Millet (*Panicum miliaceum and Eleusine corocana*) is of significance importance. They are adaptable to marginal lands, resilience to drought and nutritional benefits [23]. Millet is a staple food for many rural communities. It offers a significant source of food security and livelihood.

Its significance extends beyond its role as a food crop. It is a crucial component of the traditional agricultural systems. They often grown in intercropping systems with legumes and other cereal crops. The ability of this crop to thrive in poor soils with minimal inputs makes it a sustainable choice for smallholder famers [11]. Mainly in areas with erratic rainfall and degraded soils, it proved to be beneficial. This research focuses on analyzing land suitability for millet cultivation across different regions of Nepal using advanced Geographic Information Systems (GIS) techniques. It aims to enhance the sustainable agricultural practices and improve food security [27].

Importance of Millet Production

Millet is recognized for its resilience under harsh environmental conditions. It makes it an essential crop in regions with limited water resources and poor soil quality [12]. It requires minimal inputs in comparison with other cereals, making it a sustainable choice for small-holder farmers. In addition to this, millet is rich in nutrients, providing essesntial vitamins and minerals that helps in combating malnutrition. Its cultivation supports biodiversity and helps in maintaining ecological balance.

Nutritional benefits of millet makes it more significant. As it is high in dietary fiber, essential amino acids, vitamins and minerals, including iron, calcium and magnesium, it proves to be beneficial for human health. Moreover, millet has a low glycemic index, making it suitable for indivisuals with diabetes. It also has anti-carcinogenic properties that help fight cancer-causing agents. Phenolics in millet reduce cancer risks in vitro [6]. Studies show an inverse relationship between dietary fiber and cancers of the colorectal, small intestine, oral cavity, larynx, and breast [25]. Whole grain millet fiber significantly protects against breast cancer, reducing risk by 41% in pre-menopausal women consuming at least 13 g/day compared to those with lower intake [7]. In post-menopausal women, dietary fiber helps prevent breast cancer through non-estrogenic pathways [25]. All these properties makes it an excellent food for addressing micronutrient deficiencies and improving overall health. Because of its nutritional benefits, taste and versatility in recipes such as dhido, millet is gaining popularity worldwide.

The crop's resilience and nutritional benefit highlight its potential to contribute to food security and sustainable agriculture in Nepal [10]. As awareness of millet's advantages is growing, its adoption is likely to increase. It is also supporting the livelihoods of smallholder farmers promoting a healthier diet for consumers. This shows the importance of land suitability analysis for millet to optimize its cultivation.

Trend analysis of millet production in Nepal

Millet has been cultivated in Nepal for centuries. That is why it is deeply embedded in the country's agricultural history. Traditionally, millet was a primary staple food especially in hilly and mountain region, where other cereals struggled to thrive [15]. Looking on the historical data, it shows the millet production was once widespread, with farmers relying on its hardiness to secure food supplies. However, over these years, cultivation area and production levels have fluctuated due to various socio-economic and environmental factors.

In recent decades, millet production in Nepal has witnessed both growth and decline. According to the data from 2000/2001 to 2021/2022, millet production has shown a general upward trend despite some fluctuations. For example, production has increased form 282,852 metric tons in 2000/2001 to 339,462 metric tons in 2021/2022. However, the area of cultivation has remained relatively stable only with slight variations. Productivity of millet has also improved, increasing from 1.09 metric tons per hectare in 2000/2001 to 1.27 metric tons per hectare in 2021/2022 [21].

This trend indicates an improvement in millet farming practices over these 22 years. This is possibly due to better access to improved seed varieties, agronomic practices, and extension services. Farmers are adopting more efficient cultivation techniques and optimizing resources which increases the overall productivity. Nevertheless, the stability in the area of cultivation highlights need for appropriate policies and intervention to expand areas.

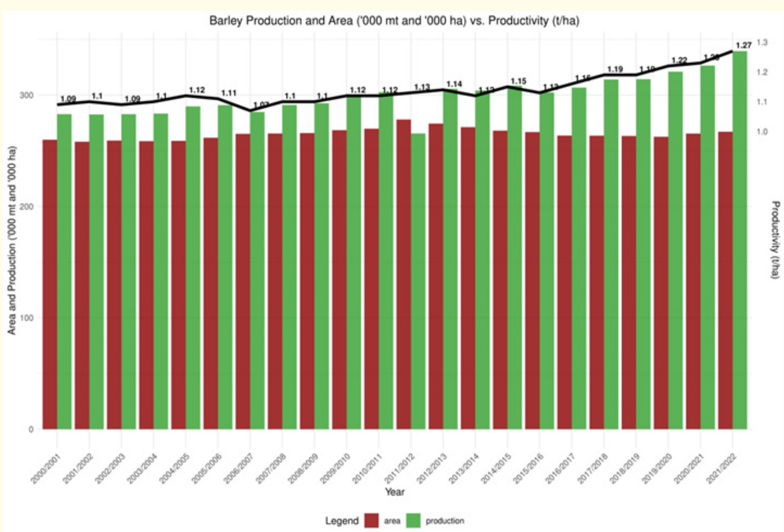

Figure 1: Barley Production and Area vs Productivity.

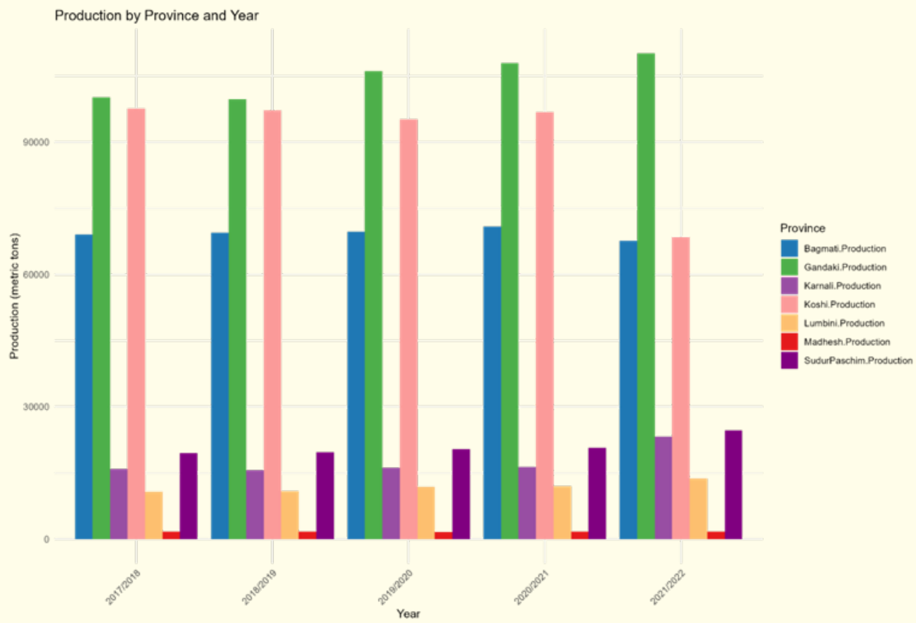

Figure 2: Production of Millet on Different Provinces.

Millet cultivation and agricultural sustainability

Environmental benefits on millet

Millet cultivation offers numerous environmental benefits, making it sustainable choice for agriculture. It requires low amount of water that reduces the strain on the water resources, especially in arid and semi-arid regions. The deep-root system of millet helps prevent soil erosion and improves soil structure by enhancing organic matter content. It also contributes to biodiversity by providing habitat and food for various organisms. It promotes ecological balance in agricultural landscapes.

The environmental benefits of millet are important in context of climate change and environmental degradation. The ability of millet to grow in low-fertility soils and under limited water condition makes it an idea crop for some regions. Those regions are areas facing water scarcity and soil degradation. Millet also supports biodiversity providing a habitat for various organisms. This crop is often grown in mixed cropping systems with legumes and other cereals. It results in the promotion of diverse of agricultural landscape and makes agricultural systems more sustainable. Mixing millet in crop rotations and intercropping systems can improve soil health and productivity as well.

Socio-economic impact

Millet cultivation has a significant socio-economic impact on rural communities in Nepal. It provides a source of income and livelihood for smallholder famers contributing to poverty alleviation. Millet-based agro-industries, like flour mills and food processing units, generate employment opportunities. Moreover, nutritional benefits of millet enhance food security and improve the health of rural populations, addressing issues of malnutrition.

Majority of smallholder farmers rely on millet for their income and food security. Millet is mainly grown on marginal lands that are unsuitable for other crops [9]. It provides a valuable source of income for farmers with limited resources. The resilience of this crop makes it a reliable food source, reducing the risk of food insecurity.

Agro-based industries of millet also contribute to the rural development. It creates employment opportunities and add value to the crop. Processing of millet into flour, snacks and other products, can increase its market value. In addition to this, it provides additional income for farmers. Its nutritional benefits enhance food security providing essential nutrients that are often lacking in diets of rural people. Promotion of millet cultivation, rural communities can improve their livelihoods and overall well-being.

Challenges and opportunities

Although it has many benefits, millet cultivation faces several challenges. It includes limited access to improved seeds, inadequate extension services and market constraints. Government agencies, research institutions and development organization need to address these challenges. Awareness campaigns, value addition and market linkages need to get promoted to overcome these issues [24].

Main challenge in millet cultivation is lack of access to improved seed varieties. Farmers often rely on traditional seed varieties. These varieties might have lower yields and be more susceptible to pests and diseases. So, distribution of high-quality seeds and training related to it can enhance millet productivity [28]. Farmers can improve their yields and income if extension services get strengthened. Market linkage development and value chains can also help farmers to sell their produce at fair prices and reduce market risks [16].

Another challenge that often receives insufficient attention in the cultivation of crops is the accurate conduct of land suitability analysis. It is essential for the identification of the appropriate areas, considering biophysical and socio-economic factors. However, different problems hinder effective land suitability analysis. Problems include limited data availability, inadequate GIS infrastructure, and insufficient technical expertise. Advanced GIS techniques improves land assessment and helps in optimization of land use.

Additionally, this analysis must address the issues related to soil fertility, water availability, and climatic conditions. In Nepal, soil fertility has been a major concern with many rural farmers. They mainly experiences declining soil productivity due to fertility depletion, nutrient imbalances and reduced organic matter.

GIS in agricultural land suitability

Geographic Information System (GIS) is an effective tool for spatial analysis and decision-making in agriculture. It integrates various types of data, such as satellite imagery, soil maps and climatic data. It helps in analyzing spatial relationships and patterns [32]. This technology enables the visualization and interpretation of complex data sets. It facilitates informed decision-making for land use planning and agricultural development [19].

GIS technology has revolutionized the way of assessing the agricultural land suitability. It allows for the integration and analysis of diverse data sets. It provides a detailed understanding of the factors affecting crop growth. GIS can analyze spatial relationships and patterns, helping identify areas with the highest potential for crop cultivation. This information is important for agricultural planning and decision-making [19]. It enables policymakers and farmers to optimize land use and resources allocation.

Application of GIS in agriculture

GIS technology has numerous applications in agriculture. It includes crop monitoring, yield prediction and land suitability analysis [17]. Analyzing the spatial data, it helps to identify optimal areas for crop cultivation based on factors like soil type, typography and climate. It aids in precision farming providing information on different factors. Those factors include soil health, water availability and pest infestation to make data-driven decisions.

This technology can track the growth and health of crops using satellite imagery and remote sensing data in case of crop monitoring. This information can be used to identify areas of poor growth or disease outbreaks. That enables timely interventions and prevent crop loss [20]. Yield prediction models can also be developed using GIS, helping famers forecast crop production and plan accordingly. It also supports precision farming, providing detailed information on soil health, pest infestation and water availability. It can be used to develop site-specific management practices, improving crop yields. Integrating GIS with other technologies, such as remote sensing and GPS, farmers can monitor and manage their fields more effectively [1]. It might results in increased productivity and sustainability.

Importance of land suitability analysis

Land suitability analysis in important for sustainable agricultural development. It involves evaluation of the potential of land for specific crop keeping basis on biophysical and socio-economic criterias. This evaluation helps in identifying suitable areas for cultivation that minimizes the risk of crop failure and maximize the productivity. According to [4], land evaluation is important process for matching selected land qualities with land use requirements. The diversity and complex features of land quality, significantly impact its suitability for specific uses. [26] defined land quality as the fitness for use and soil's ability to function [13].

Main importance of land suitability analysis lies in its ability to optimize land use and resources allocation to maximize production. Identification of the most suitable areas for specific crops like millet, farmers can minimize the risk of crop failure [3]. Efficient land use is essential for food security and sustainable development, mainly in those regions where there is limited resources [8]. GIS-based land suitability analysis provides better understanding of the factors affecting crop growth. It enables targeted interventions and efficient resources allocation. Multi-criteria Descsion Making (MCDM) or Multi-criteria Evaluation (MCE) are also effective tools for multiple criteria descsion making issues. They can evaluate alternatives based on the conflicting criteria [18].

Land suitability analysis supports sustainable agricultural practices as well. It helps in identifying areas with high potential of crop cultivation and minimizing the impact on natural resources. Farmers can minimize the environmental impact of agriculture and promote sustainable development by optimizing land use. This initiation is important in region facing environmental challenges such as water scarcity and soil degradation [2]. GIS-based land suitability analysis provides authentic information for the development of sustainable agricultural strategies and improving food security. GIS aids in manipulating assessment factors, while MCE integrates them into suitability maps, facilitating informed descison-making processes for land-use planners [17].

In Nepal, soil water conservation and soil fertility enhancement have been important subjects of considerable research [29]. However, declining soil fertility remains main concern for most of the farmers [31]. The adoption of improved techniques has been limited in case of Nepal [2]. Soil productivity has declined due to fertility depletion, nutrient imbalances. As consequences, there is reduced organic matter, which degraded the soil's physical and chemical properties. The effectiveness of combining MCE with GIS in evaluating suitable land crops in Nepal [22]. It highlights the importance for aggregating socio-economic and environmental data.

Therefore, land suitability analysis is a critical tool for ensuring sustainable agricultural development. Using GIS and MCE, this analysis provides detailed understanding of the spatial variability of factors affecting crop growth. This enables targeted interventions, efficient resource allocation and development of sustainable agricultural strategies. It ultimately, improves the food security and supports the livelihoods of rural communities.

Methodology

Study Area

The study area for this study is landscapes of Nepal. Specifically it examines regions of Nepal that span over the Terai, Hill and Mountain Zones. This area stretches from latitude 26°20'N to 30°26'N and longitude 80°03'E to 88°12'E. It covers broad spectrum of altitudinal ranges from low-level terai plains at about 60 meters above sea level to the Himalayan peaks exceeding 8000 meters.

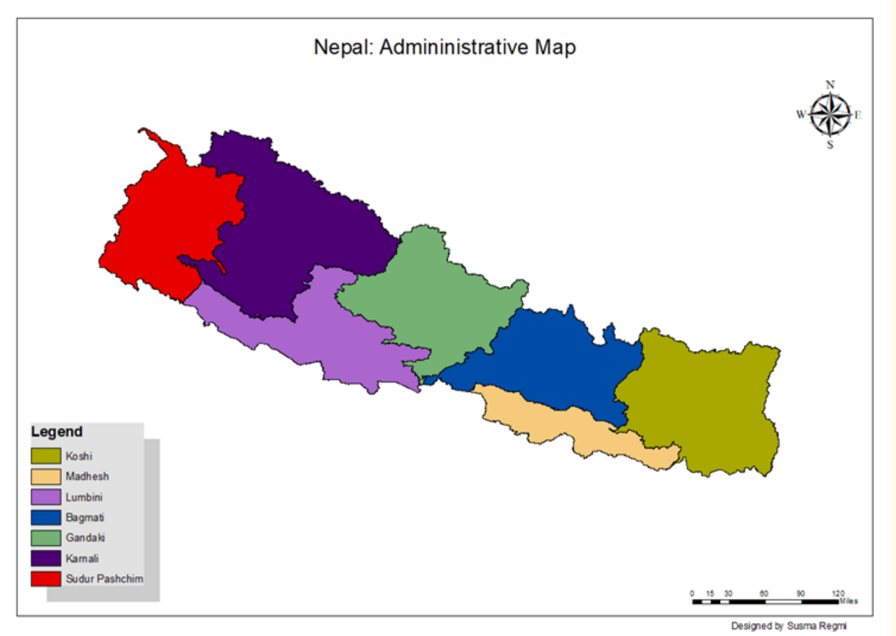

Figure a

The diverse geographic setting includes districts such as Jhapa, Morang and Sunsari in Terai; Dhading, Gorkha and Lamjung in the Hills; and Mustang and Dolpa in the Mountains. Each of these regions shows unique climatic conditions, soil types and topographies that is essential for analysis of millet cultivation suitability.

The terai region has a lot of hot and humid subtropical climate, dominated by the monsoon season; with annual rainfall ranging from 1500 to 2500 mm. In comparison, the hill region has a temperate climate with moderate rainfall between 1000 and 2000 mm annually. The mountain region has alpine climatic condition, characterizing lower temperatures and variable precipitation patterns, often exceeding 3000 mm annually. This area is not only geographically diverse but also socio-economically significant. It consists of a population primarily engaged in agriculture, with many depending on subsistence farming. The different agricultural practices and socio-economic conditions provide a rich context for the evaluation of millet cultivation suitability.

Data sources and acquisition

GPS Device

It was used for field surveys to collect precise geographical coordinates. This data was crucial for ground-truthing and validating remote sensing and GIS-based analyses.

Land use and land cover map

This was obtained from Department of Survey, Nepal. Those maps provide information on various land cover types, including agricultural land, forests, water bodies, and urban areas.

Soil data

Soil data was obtained from the Soil and Terrain Database (SOTER). Soil data includes information on soil type, texture, depth and fertility. Soil characteristics are important factors influencing crop growth and yield.

Climate data

Digital elevation model (DEM)

Digital Elevation Model (DEM) provide elevation data, which was used to derive slope and aspect information. These topographical parameters are essential for obtaining information of terrain and its suitability in agriculture.

Software tools

ArcGIS 10.1 was used for spatial analysis and creating suitability maps. MS Excel 2013 was employed for data management, AHP and MCD analysis. Google Earth Pro was used for the digitization and verification of spatial features.

Variable identification

A review of various sources identified the main variables influencing millet cultivation. Agricultural experts, local farmers, and field verification confirmed these variables. The identified variables included:

Elevation

Growth of Millet is mainly influenced by Altitude. It also affects temperature and other climatic conditions [14]. The orientation of the slope affects sunlight exposure and also microclimatic conditions.

Slope

The gradient of the land impacts soil erosion, water drainage, and mechanization feasibility as well.

Soil type and pH

Various soil types have varying capacities to support millet growth. It mainly depends on their texture, fertility, and drainage properties.

Land cover

Vegetation and land cover types influence soil properties and microclimate.

Land forms

Optimal landforms for cultivation are necessary for millet growth and development. It mainly influences microclimates, water availability and soil properties.

Total nitrogen

This is essential nutrient for plant growth. It mainly influences vegetative growth and grain production. Appropriate nitrogen levels in the soil are critical for the overall health and yield of the millet.

Precipitation

Adequate and timely rainfall is essential for millet cultivation.

Suitability assessment

Limitation	Rating	Land suitability index
0: No	100-85	S1
1: Slight	85-60	S2
2: Moderate	60-40	S3
3: Severe	40-25	N1
4: Very Severe	25-0	N2

Table 1: Suitability classes for land index.

Source: [30].

In conducting this research, primary focus was on classification of land into five categories. They are: highly suitable, moderately suitable, marginally suitable, actually not suitable but potentially suitable and actually or potentially unsuitable. However, for practical analysis and visualization purpose, fifth criteria was merged with fourth one to enhance the clarity of the suitability map.

The fourth category covers glaciers and snow-covered regions, which aren't suitable for millet cultivation. For better analysis and visualization, we merged these regions with the fifth category. This approach clarifies the suitability map and shows areas where actionable improvements can be made.

Spatial Distribution of Suitability

The spatial distribution of suitability for millet cultivation showed significant variability among different regions of Nepal (Table 2). High suitability and moderate suitability areas were primarily located in regions with gentle slopes, fertile soils and adequate rainfall. Marginal suitability areas were distributed across different topographical and climatic zones. They mainly shows the diverse potential for millet cultivation in Nepal.

Parameters	Rating
Elevation	600-2000
Slope	0-5
Organic Matter	3-9%
Soil pH	6-7.6
Soil Type	Loamy fertilie, sandy loam
Land Cover	Grassland, cropland, forest area
Total Nitrogen	0.5-1.0%
Land forms	Plain, valley floor, low gradient footslope
Precipitation	500-1200

Table 2: Climate and soil requirements range for millets.

Variable influence assessment

Pairwise comparison matrix

Major nine variables having key impacts on cultivation of millet were identified (Table 3). After identification, each variable is paired with another variable and a comparison is made. This was done on the basis of their importance for the cultivation of barley crop mentioning on the scale of 1 to 9 where 1 represent equal importance and 9 represent extreme importance of one over another. This scaling was done on the basis of Saaty scale of pairwise comparison. For instance, Soil type is more important than Elevation as value is 7. So, soil type and elevation pair is 0.14 value i.e. 1/7.

Variables	Elevation	Slope	Organic Matter	Soil pH	Soil type	Land cover	Total Nitrogen	Land forms	Precipitation
Elevation	1	3	2	3	3	3	4	8	8
Slope	1/3	1	3	3	2	2	3	7	7
Organic Matter	1/2	1/3	1	3	4	3	4	6	6
Soil pH	1/3	1/3	1/3	1	3	2	3	5	4
Soil type	1/3	1/2	1/4	1/3	1	3	5	4	3
Land cover	1/3	1/2	1/3	1/2	1/3	1	3	2	5
Total Nitrogen	1/4	1/3	1/4	1/3	1/5	1/3	1	3	2
Land forms	1/8	1/7	1/6	1/5	1/4	1/2	1/3	1	3
Precipitation	1/8	1/8	1/6	1/4	1/3	1/5	1/2	1/3	1
Sum	3.33	6.27	7.50	11.62	14.12	15.03	23.83	36.33	39.00

Table 3: Pairwise comparison matrix.

Out of major nine influencing variables, five variables i.e. elevation, slope, organic matter, soil pH, soil type have more influence with weight 26%, 19%, 17%, 11%, 10% respectively, whereas land cover, total Nitrogen, landforms and precipitation has low influence with weight 7%, 4%, 3%, 2% respectively.

Normalization

The pairwise comparison matrix was normalized (Table 4) using the Ms. Excel. Also, after performing normalization, weight for each variable were calculated by averaging the normalized values in each row. The weights represent relative importance of each variable in determining millet suitability.

Variables	Elevation	Slope	Organic Matter	Soil pH	Soil type	Land cover	Total Nitrogen	Temperature	Land forms	Criteria Weights	Weights %
Elevation	0.30	0.48	0.27	0.26	0.21	0.20	0.17	0.22	0.21	0.26	26
Slope	0.10	0.16	0.40	0.26	0.14	0.13	0.13	0.19	0.18	0.19	19
Organic Matter	0.15	0.05	0.13	0.26	0.28	0.20	0.17	0.17	0.15	0.17	17
Soil pH	0.10	0.05	0.04	0.09	0.21	0.13	0.13	0.14	0.10	0.11	11
Soil type	0.10	0.08	0.03	0.03	0.07	0.20	0.21	0.11	0.08	0.10	10
Land cover	0.10	0.08	0.04	0.04	0.02	0.07	0.13	0.06	0.13	0.07	7
Total Nitrogen	0.08	0.05	0.03	0.03	0.01	0.02	0.04	0.08	0.05	0.04	4
Land forms	0.04	0.02	0.02	0.02	0.02	0.03	0.01	0.03	0.08	0.03	3
Precipitation	0.04	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.03	0.02	2
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		

Table 4: Normalized Matrix for Weightage Calculation.

Weight calculation

The weighed overlay analysis was done using ArcGIS 10.1. Each variable was assigned a weight based on its relative importance as determined by comparison matrix. Then, these variables were combined using a weighted sum approach to generate a composite suitability map.

Consistency check

Consistency index (CI) of 0.086817 was found through the test of consistency test with maximum Eigen value 9.69 for the nine variable. From the ration of consistency index and random consistency index, consistency ration was also calculated. The consistency ration was found 0.059, which is less than 0.1 that proves the matrix is consistence enough.

Suitability map generation

Suitable maps were generated through ArcGIS 10.1 for each variables. In addition to this, combined analysis was done using the Weight of Pairwise comparison matrix.

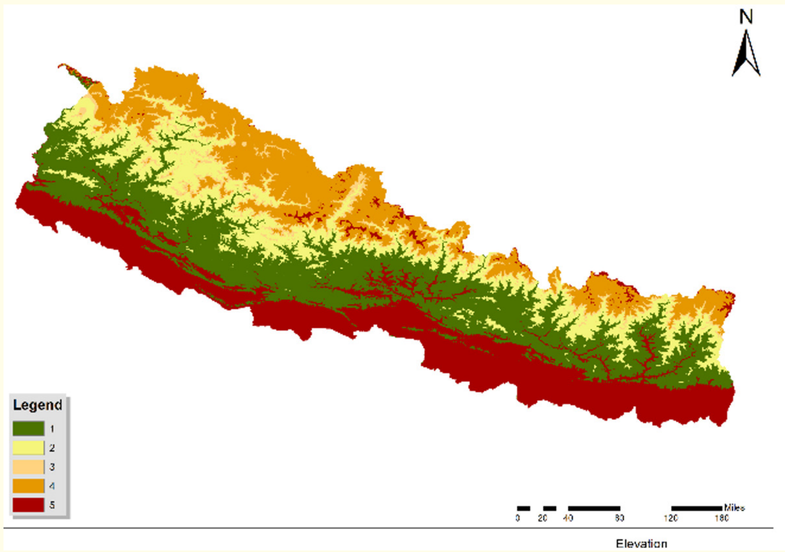

Figure 3: Classified spatial variation of Elevation.

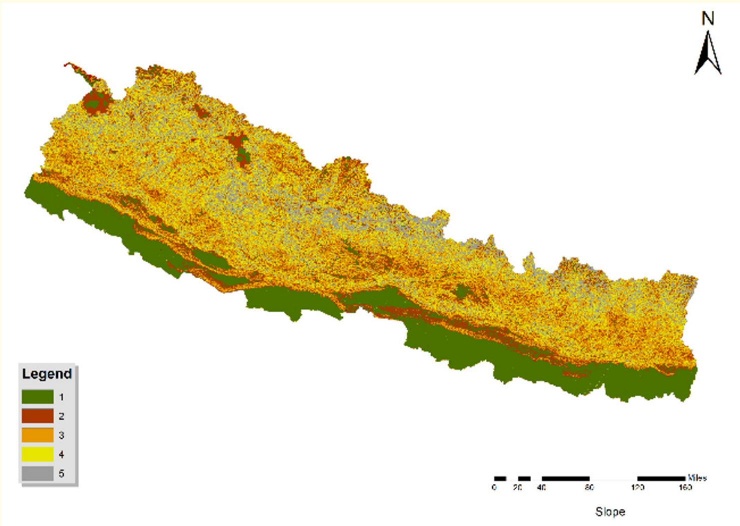

Figure 4: Classified spatial variation of Slope.

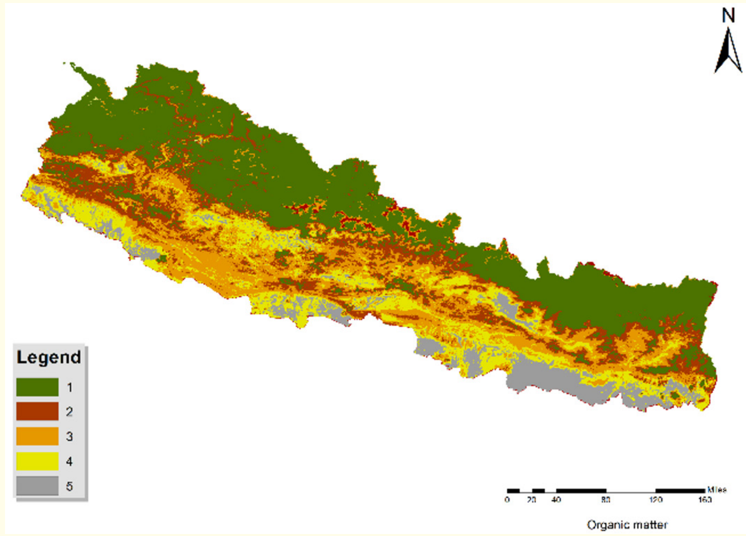

Figure 5: Classified spatial variation of Organic Matter.

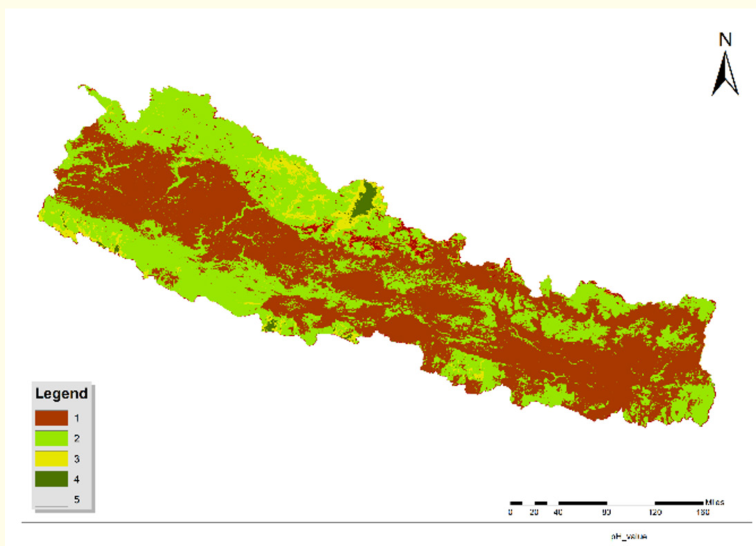

Figure 6: Classified spatial variation of Soil pH.

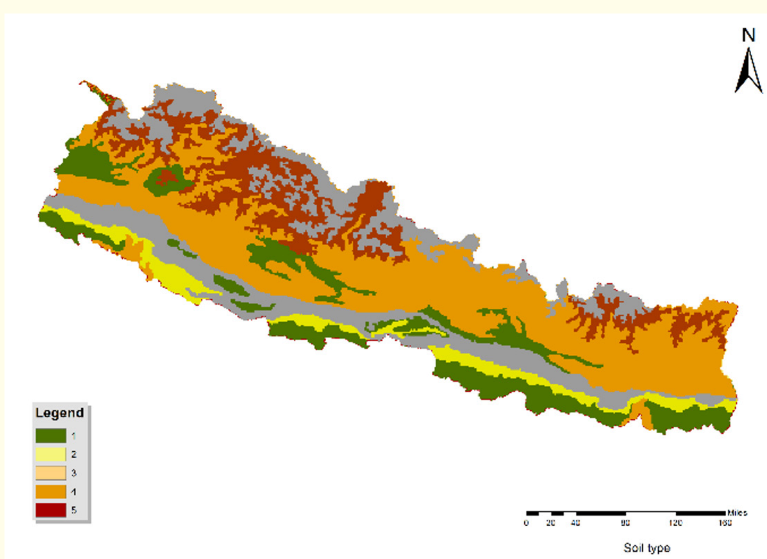

Figure 7: Classified spatial variation of Soil type.

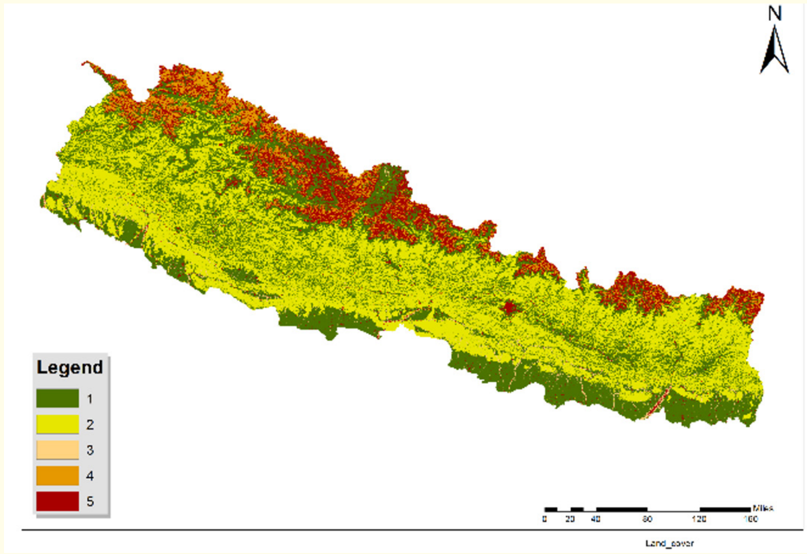

Figure 8: Classified spatial variation of Land cover.

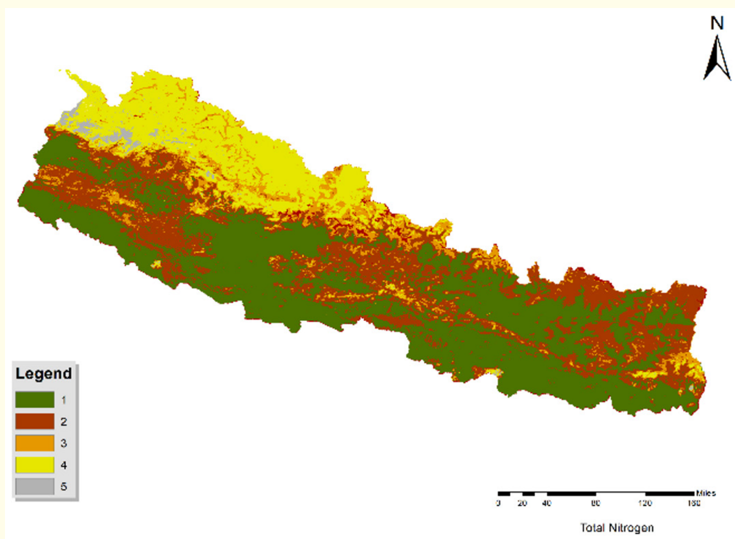

Figure 9: Classified spatial variation of Soil Nitrogen.

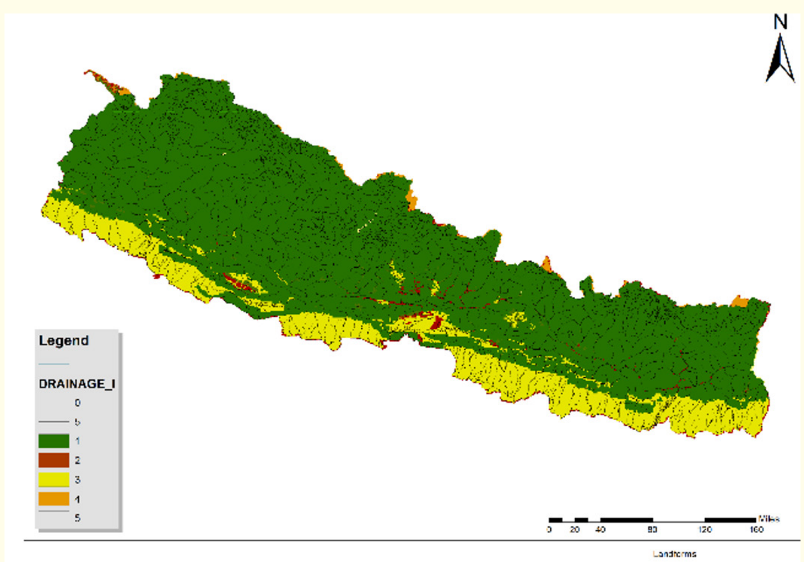

Figure 10: Classified spatial variation of Landforms.

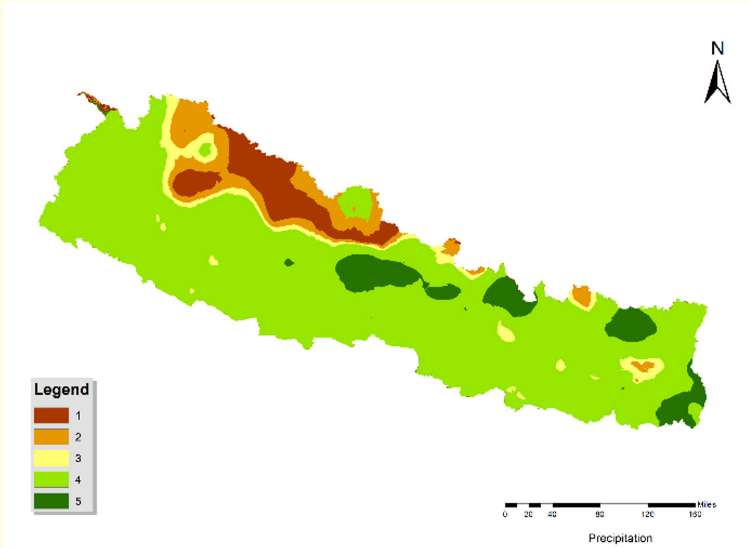

Figure 11: Classified spatial variation of Precipitation.

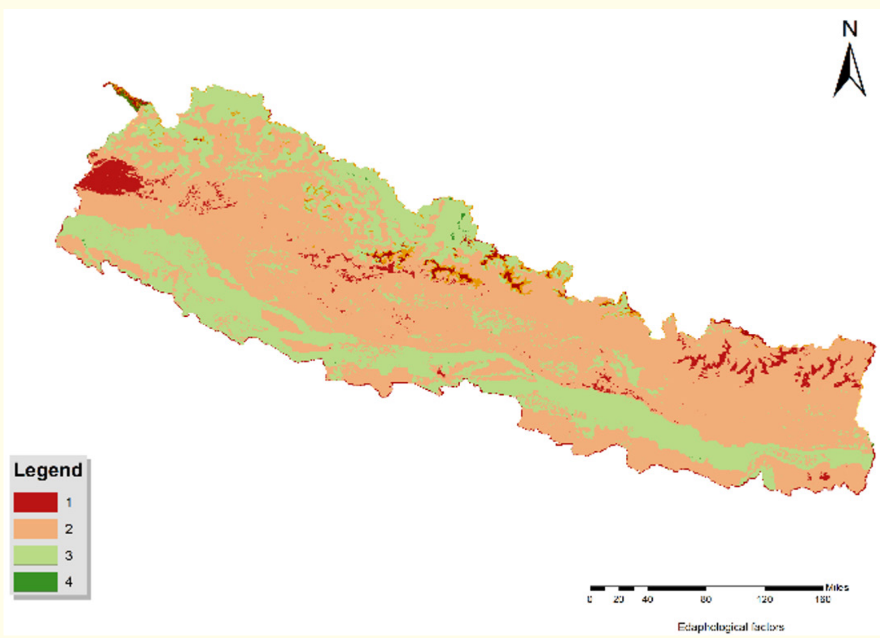

Figure 12: Classified spatial variation of Edaphological Factors.

Discussion

The results of the suitability analysis provide valuable information into the potential for millet cultivation across different regions of Nepal. The suitability map shows areas with high, moderate, and low suitability for millet, helping farmers make informed descisons about land use and crop planning.

High suitability areas (S1)

These areas have optimal conditions for millet cultivation. It includes suitable elevation, gentle slopes, favourable aspect, fertile soil, appropriate land use, adequate temperature, and sufficient precipitation. High suitability areas are ideal for expanding millet cultivation and increasing production. This area was accounted for 0.45% of the total area analyzed.

Moderate suitability areas (S2)

These areas have conditions that are generally favorable for millet cultivation but require some management practices to optimize yield. For instance, areas with moderate slopes or less fertile soil may benefit from soil conservation measures, fertilization and irrigation. Moderate suitability areas constituted 51.24% of the total land.

Marginal suitability areas (S3)

These particular areas have condition that are less favorable for millet cultivation. They may pose some significant challenges for farmers. Marginal suitability areas may include steep slopes, less favorable aspects, or areas with suboptimal soil and climate conditions. Despite these challenges, with appropriate interventions such as soil amendments or terracing, these areas could get more productive. This areas covered 46.93% of the total land.

Currently not suitable areas (S4)

These ones are currently unsuitable for millet cultivation due to unfavorable conditions. For example. Steep slopes, poor soil quality, or extreme climate. However, with appropriate management and technological uses, some of these areas may get converted to marginal or moderately suitable lands in the future.

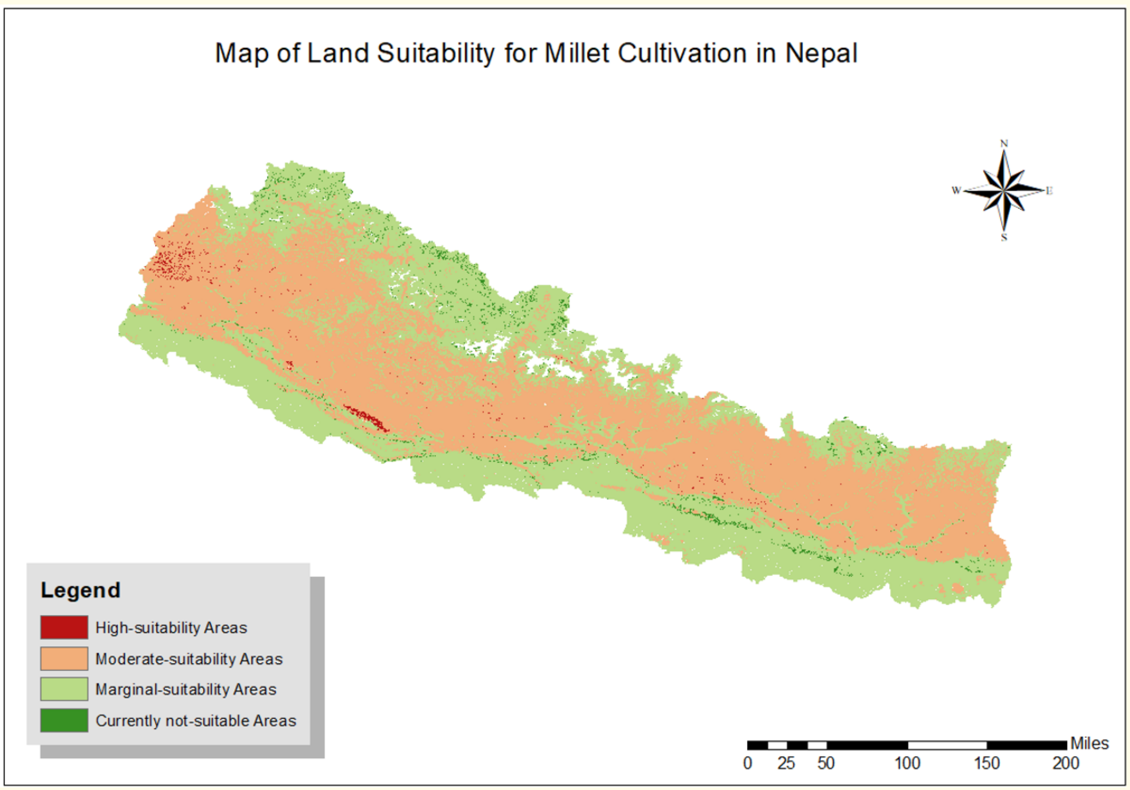

Figure 13: Overall Classified Spatial Variation of Millet Cultivation.

Values	Percent (%)
High-suitability areas	0.45
Moderate-suitability areas	51.24
Marginal suitability areas	46.93
Currently not suitable	1.4

Table a

Data sources and indicators

Elevation affects the rate and magnitude of erosion. It is a significant factor in determining the land suitability.

Challenges and opportunities

Many challenges were faced while conducting this research. One of the main problem was limited availability of detailed and accurate data for land suitability analysis.

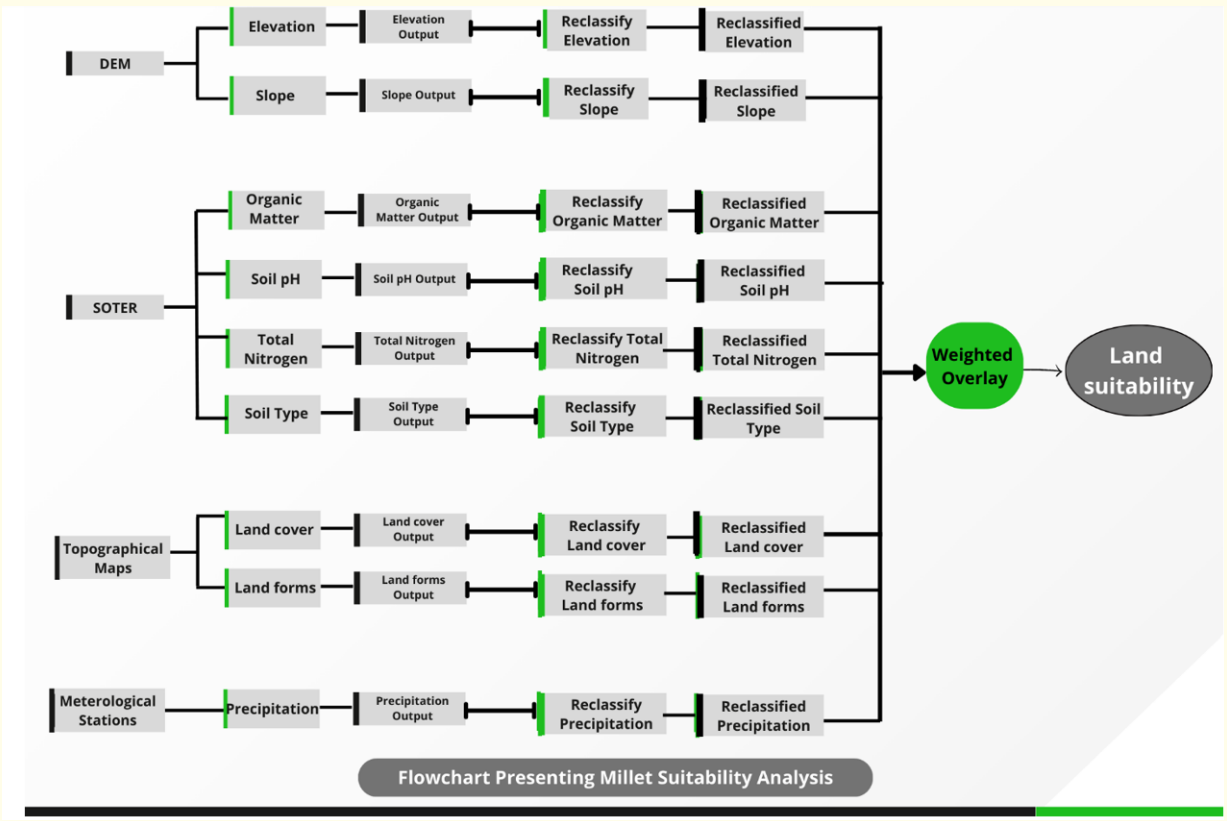

Figure 14: Flowchart presenting Millet suitability analysis.

Though, there are many opportunities of this research. For instance, formulation of policies to support millet cultivation including subsidies for improved seeds and fertilizers. Also, providing training to farmers on best practices for its cultivation, teach farmers to use GIS and remote sensing-like technologies for suitability assessments and optimization of land use.

Conclusion

The land suitability analysis for millet cultivation across different regions of Nepal provide valuable information regarding optimization of land resources. It might enhance sustainable agricultural practices and improves food security. The suitability map identifies areas with high, moderate, and low suitability. It helps farmers make informed decisions regarding land use and crop planning. This study also highlights the potential for expanding millet cultivation in high suitability areas and moderately suitability areas. Addressing the identified challenges and acknowledging opportunities, this cultivation of millet can get optimized.

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