

Suitability of Green Gram Production in Kenya under Present and Future Climate Scenarios Using Bias-Corrected Cordex RCA4 Models

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Abstract

Green gram is considered as one of the legumes suitable for cultivation in the Arid and Semi-Arid Lands (ASALs) of Kenya. However, climate change may alter the areas suitable for green gram production. This study sought to model green gram suitability in Kenya under present and future conditions using bias-corrected RCA4 models data. The datasets used were: maps of soil parameters extracted from Kenya Soil Survey map; present and future rainfall and temperature data from an ensemble of nine models from the Fourth Edition of the Rossby Centre (RCA4) Regional Climate Model (RCM); and altitude from the Digital elevation model (DEM) of the USGS. The maps were first reclassified into four classes of suitability as Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Not Suitable (N). The classes represent the different levels of influence of a factor on the growth and yield of green grams. The reclassified maps were then assigned a weight generated using the Analytical Hierarchy Process (AHP). A weighted overlay of climate characteristics (past and future rainfall and temperature), soil properties (depth, pH, texture, CEC, and drainage) and altitude found most of Kenya as moderately suitable for green gram production during the March to May (MAM) and October to December (OND) seasons under the baseline, RCP 4.5 and RCP 8.5 scenarios with highly suitable areas being found in Counties like Kitui, Makeni, and West Pokot among others. During the MAM season, the area currently highly suitable for green gram production (67,842.62 km²) will increase slightly to 68,600.4 km² (1.1%) during the RCP 4.5 and reduce to 61,307.8 km² (-9.6%) under the RCP 8.5 scenario. During the OND season, the area currently highly suitable (49,633.4 km²) will increase under both RCP 4.5 (22.2%) and RCP 8.5 (58.5%) scenarios. This in-

crease is as a result of favourable rainfall and temperature conditions in the future.

Keywords

Climate Change, Green Gram, Kenya, Rainfall, Soil, Suitability, Temperature, Topography

1. Introduction

Over 80% of Kenyan land is classified as ASALs and is considered as being the most susceptible to the effects of climate change and variability [1]. The ASAL regions of Kenya are characterised by low rainfall that varies in space and time. These areas also experience prolonged dry seasons with high evapotranspiration rates [1]. Climate in its spatial and temporal variability is one of the major drivers determining agricultural productivity in a region.

There is general agreement that climate is changing, and that the agricultural sector among others will be affected under future climates. Climate change may have an impact on both the ASAL and high potential areas in Kenya making present agricultural use unsuitable. Climate-smart agriculture either by growing drought-resistant crops or supplementing rainfall with irrigation can help the country generate income, employment, and attain food security. To develop long-term agricultural policies, planners need to understand the likely impacts of climate change on agricultural suitability zones [2].

Green gram (*Vigna radiata* L.), is a short duration (65 - 90 days) grain legume grown on more than 6 million hectares globally in the warm areas [3] [4]. Green gram is native to the Indian subcontinent [4], but also grown in the dry and hot regions of Eastern Africa, Southern Europe and Southern United States [5], and reported to have spread early into other Asian countries and to northern Africa. India is the largest consumer and producer of green grams, accounting for 54% and 65% of world consumption and acreage respectively.

Green gram is considered as a legume suitable for cultivation in the ASALs due to its ability to perform well under the dry conditions found in the semi-arid regions [6]. Since green gram performs well in dry conditions, with this dryness expected to worsen with future climate change, green gram may be a better crop for subsistence farmers to survive the expected effects of climate change. Planting green grams where it is best suited will bring more returns to farmers, enhance food security, and increase food production [7]. To enhance the productivity of green grams, there is need to develop a suitability map.

Crop suitability analysis helps determine which areas are currently suitable and whether they will remain so in the future, which is critical for policy regarding the future [8]. Ahmed and Fayyaz-Ul-Hassana [9] recommended using suitability ratings to rank crop production potential based on different ranges in

the climate, terrain, and soil of the land. Decision-makers are usually engaged to determine which factors they consider most important for suitability analysis using Multiple Criteria Decision Analysis (MCDA); the results are then used in GIS as weights for the suitability analysis. The Analytical Hierarchy Process (AHP) is the most used MCDA method to weigh the factors that decision-makers consider most important for suitability analysis [7]. Several studies have carried research on crop suitability for various crops using the AHP method [7] [10] [11] [12] [13].

Mugo *et al.* [14] found some areas in Kitui County, an ASAL region in Kenya, suitable for production in terms of climate. There is, however, a lack of knowledge on whether other ASAL areas in Kenya are currently suitable for green gram production, and how climate change will affect their current suitability. This study used a bias corrected multimodel ensemble of rainfall and the multimodel ensemble of mean temperature to carry out the analysis. The process of bias correcting the rainfall data is described in a previous paper by Mugo *et al.* [15]. This study shall determine which areas in the ASAL regions in Kenya would best support green gram production under baseline (1971-2000) and future (2021-2050) climate conditions for the Representative Concentration Pathways (RCP) 4.5 and 8.5.

2. Materials and Methods

2.1. Study Area

Kenya (**Figure 1**) lies between latitudes 5°N and 5°S and longitudes 34°E and 42°E and has an area of approximately 584,000 km². Kenya's rainfall and temperature pattern is mainly bimodal and is controlled by the location of the Inter-Tropical Convergence Zone (ITCZ). The seasonal migration of the sun which is overhead the equator in March and September and the position of the ITCZ affect the rainfall pattern observed from May to May (MAM) and October to December (OND). The cloud cover influences the observed temperature by lessening the incoming solar radiation and outgoing terrestrial radiation.

Kenya's climate is also affected by its varying topography and the presence of large water bodies. Kenya's elevation increases from the coastal plateau toward central Kenya where Mount Kenya is located. The presence of Mount Elgon and Mount Kilimanjaro put the western part of the country at a higher elevation compared to the eastern part. Large water bodies include the Indian Ocean in the east and Lake Victoria in the west. Rainfall in Kenya has high variability across different regions, with the ASALS experiencing the highest variability in time and space.

The ASALs which make up 80% of Kenya's total landmass are characterised by high poverty levels, low illiteracy levels, human conflict, poor infrastructure, and land degradation [16]. The ASALs are also prone to floods; despite receiving low levels of rainfall of 300 - 500 mm annually [1]. Periods of intensive rainfall have been observed to follow the droughts [17]. However, despite the challenges

mentioned, the ASALs are rich in natural resources amid them being wildlife, biodiversity, minerals, and diverse culture [16].

2.2. Data Description

Secondary digital databases were acquired from various sources as shown in (Table 1). The secondary databases were: maps of soil parameters extracted from Kenya Soil Survey map; present and future rainfall and temperature data from a bias corrected ensemble of nine RCA4 models from the Fourth Edition of the Rossby Centre (RCA4) Regional Climate Model (RCM) [18]; and altitude from the Digital elevation model (DEM) of the USGS.

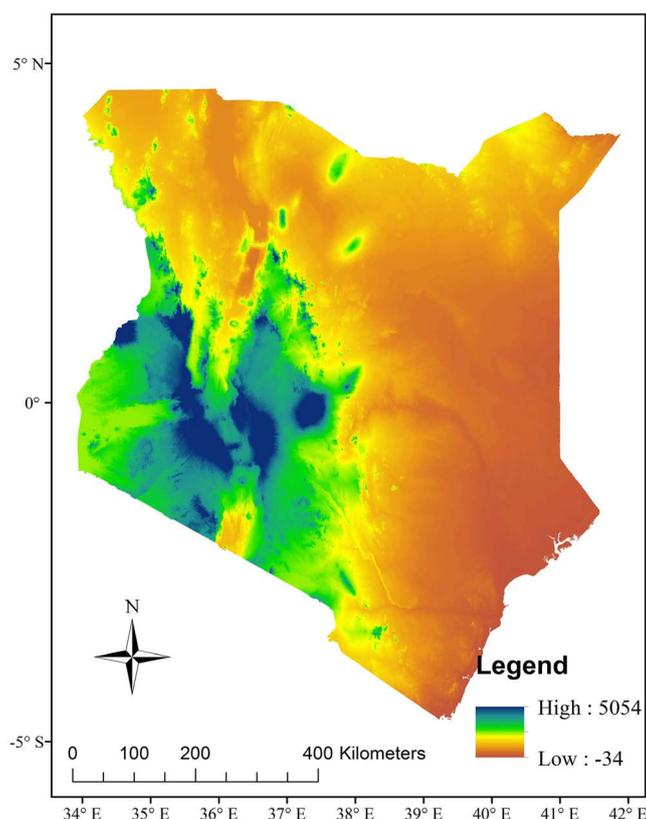


Figure 1. Topography of the study area (in meters). The blue regions show areas of high elevation decreasing through to the brown regions.

Table 1. Description of secondary data sources used as map layers in delineating areas suitable for green gram production.

Data layer	Source	Scale/Resolution	Data Format
Climate: Temperature and rainfall	CORDEX RCA4 model	0.44 degrees/50 km	NETCDF format and converted to Raster format
Soil: pH, CEC, depth, drainage, and texture	Kenya Soils Survey		Vector format and converted to Raster format
Topography/DEM: Altitude	United States Geological Survey (USGS)	30 m	Raster format

2.3. Methodology

2.3.1. Suitability Criteria Assignment and Reclassification of Data

The data on climatic, soil, and altitude was first categorized into two classes, suitable and not suitable. The two classes were further divided into four classes namely, Highly suitable (S1), Moderately suitable (S2), Marginally suitable (S3), and not suitable (N) as guided by **Table 2**. **Table 3** shows the four classes of suitability in terms of green gram production. The classes represent the different levels of influence of a factor on the growth and yield of green grams.

Table 2. Land suitability classification structure source: [19].

Order	Class	Description
S	S1	Land that has no significant limitations to the continued application of a given use, or only minor limitations that will not remarkably reduce productivity and benefits and will not raise inputs above an acceptable level.
	S2	Land having limitations which in total are moderately severe for continued application of a given use; the limitations will thus lower the productivity or benefits and increase the inputs required to the level that the final advantage to be obtained from the use, although still attractive, is considerably lower to that expected on Class S1 land.
	S3	Land having limitations which in total are severe for continued application of a given use and will so lower productivity and benefits, or increase required inputs, such that this expenditure is only marginally justifiable.
N	N1	Land having limitations that may be overcome in time but which cannot be rectified with existing knowledge at a currently acceptable cost, the limitations are so acute as to prevent the successful sustained use of the land in the given manner.
	N2	Land that has limitations which seem to be so severe as to surpass any chance of successful sustained use of the land in the given manner

Table 3. Suitability levels for factors used in developing suitable areas for green gram production.

	S1	S2	S3	N	Source
Rainfall	250 - 350 mm	150 - 250 mm 350 - 600 mm	75 - 150 mm >600	<75 mm	[20]
Temperature	30°C - 21°C	18°C - 21°C	15°C - 18°C	<15°C >30°C	[21]
Soil pH	6.2 - 7.2	5 - 6.2	7.2 - 8.0	>8.0 <5.0	[14] [22]
Drainage	Well-drained	Imperfectly drained	Poorly drained, Rapidly drained	Very poorly drained	[14] [23]
Texture	Loam Sandy Loam	Clayey	Very clayey Extremely sandy	-	[14] [23]
CEC	>10 meq/100g	5 - 10 meq/100g	0 - 5 meq/100g	-	[14] [22]
Depth	>50 cm	30 - 50 cm	<30 cm		[14] [23]
Altitude	0 - 1600 m	1600 - 2000 m	-	>2000 m <0 m	[14] [22]

2.3.2. Factor Weight Assignment Using the Analytical Hierarchy Process

A scale of values from 1 to 9 (Table 4) was used to compare and assign weights to factors [24] under climate (rainfall and temperature), soil (depth, pH, texture, CEC, and drainage) and altitude.

A Consistency Ratio (CR) (Equation (1)) was determined and for the weights to be accepted, the ratio was expected to be less than 10% to prevent bias [8].

$$CR = \frac{CI}{RI} \quad (1)$$

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (2)$$

In Equation (1) *CR* represents the Consistency Ratio and *RI* stands for the Random Inconsistency Index which is dependent on the number of factors being related as shown in (Table 5). In Equation (2) *CI* signifies the Consistency Index; λ_{\max} represents the maximum Eigenvalue of the pairwise comparisons, and *n* counts the number of factors being related.

2.3.3. Green Gram Suitability Map

After reclassifying the criteria maps, each was assigned a certain percentage stake (weight). These were the weights obtained through the analytical hierarchy process. The maps were then overlaid to generate the final output which is a green gram suitability map under baseline (1971-2000) and future (2021-2050) RCP 4.5 and 8.5 climate conditions.

3. Results and Discussions

3.1. Analysis of the Suitability of Land for Green Gram Production under Past and Future Climate Scenarios

This section presents results obtained from the weighted overlay of climate (past and future rainfall and temperature), soil (depth, pH, texture, CEC, and drainage), and altitude. The first step in analysing the suitability of green gram production involved reclassification of soil and climate parameters.

Table 4. Scale of relative importance between any two factors which affect green gram production e.g. rainfall vs. drainage.

Definition of Importance	Scale
Factors have equal rank	1
One factor has weak rank over the other	3
One factor has strong rank over the other	5
One factor has demonstrated importance over the other	7
One factor has absolute rank over the other	9
Intermediate values used when factor importance lies between the odd numbers	2, 4, 6, 8

Table 5. Random Inconsistency Index (RI) for N = 1, 2 ..., 11.

N	I	II	III	IV	V	VI	VII	VII	IX	X	XI
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Source: [24].

3.1.1. Reclassification of Soil and Altitude Parameters in Terms of Their Suitability for Green Gram Production

This subsection presents the results on the reclassification of soil and altitude depending on their suitability levels (Table 2). Figure 2 presents the results for the reclassification of soil and altitude parameters into four classes (S1, S2, S3, and N). In Figure 2 factors highly limiting the suitability of green gram were pH, depth, altitude, and drainage.

The pH-water is used as an index of soil suitability for crops or plants; areas not suitable can be improved through liming which can improve the overall suitability. Green gram is well adapted to a pH range of 5 to 8 [5] [25] [26]. The performance is best on soils with a pH between 6.2 and 7.2 and plants can show serious iron chlorosis symptoms and micronutrient deficiencies on alkaline soils [27]. They require slightly acid soil for the best growth [27].

Soil depth is the estimated space in centimeters where root growth is unrestricted by any physical or chemical impediment such as impenetrable or toxic layer. Areas with poor drainage can be improved upon by building fallows to improve drainage during the rainy season which can further improve suitability.

3.1.2. Reclassification of Climate Parameters (Temperature and Rainfall) Under Present and Future (RCP 4.5 and RCP 8.5) (2021 to 2050) Scenarios in Terms of Their Suitability for Green Gram Production

This subsection presents the results of the reclassification of temperature and rainfall depending on their suitability levels (Table 2) under the present and future (RCP 4.5 and RCP 8.5) (2021 to 2050) scenarios in terms of their suitability for green gram production.

According to Figure 3, most of Kenya is highly suitable for green gram production in terms of temperature. Areas that are not suitable are noted in Nyeri and Nyandarua Counties since these areas experience temperatures lower than 15°C which according to Al-Mashreki *et al.* [21] are not suitable for green gram production. Under both the RCP 4.5 and RCP 8.5 scenarios during the MAM season, areas around the Northern and Western parts of Kenya will not be suitable for green gram production since they will experience temperatures greater than 30°C. A temperature range of 28°C to 30°C is considered optimum for seed germination and plant growth [21] [27].

Figure 4 shows the areas in Kenya that are suitable and not suitable for green gram production in terms of rainfall. Areas that are not suitable for production are located around the North-West part of Kenya during the OND season, where rainfall amounts are less than 75 mm per season. Water stress reduces the rate of uptake of nutrients, flowering, leaf area development, and photosynthesis

causing yield reduction [3]. An optimum rainfall of 250 - 350 mm is considered best for sustained germination [20].

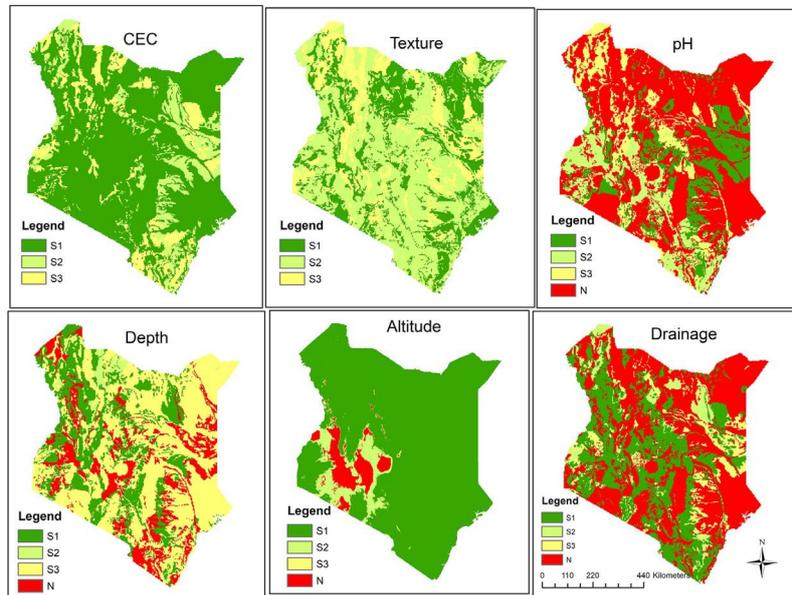


Figure 2. Reclassified maps of soil CEC, texture, pH, depth, altitude, and drainage. The green colour shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (N) represents areas that are not suitable for green gram production in Kenya based on these classifications.

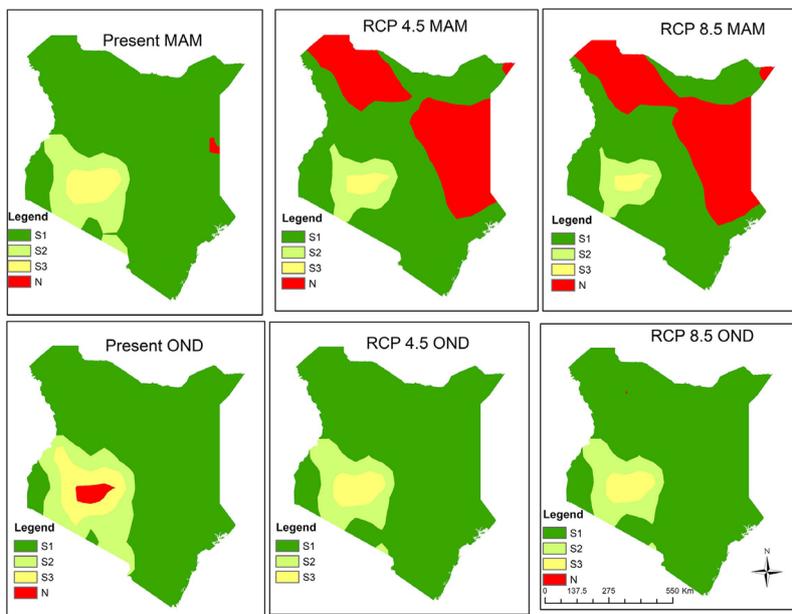


Figure 3. Reclassified maps of present and future mean temperature (in °C) layers during the MAM and OND seasons. The green colour shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (N) represents areas that are not suitable for green gram production in Kenya based on these classifications.

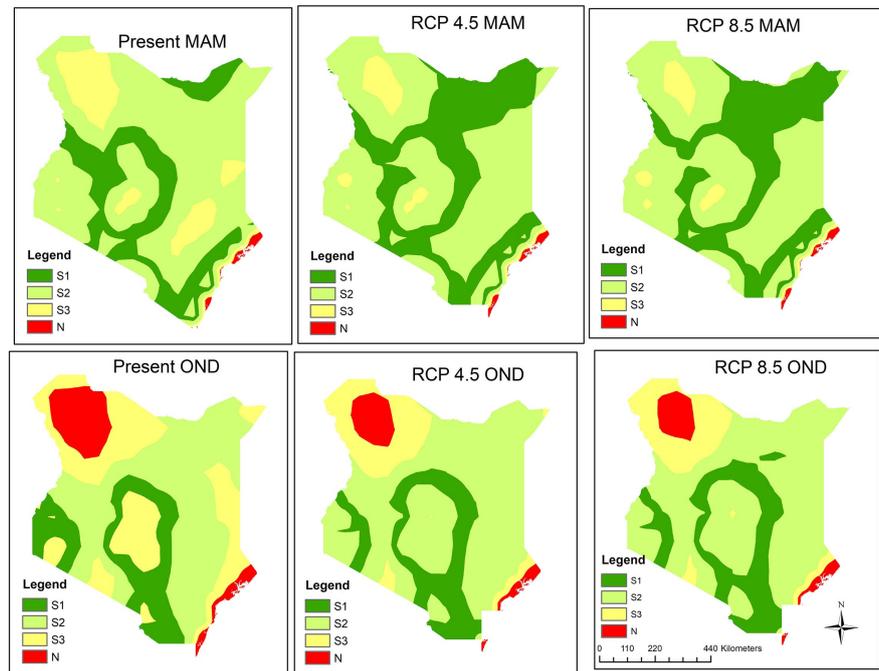


Figure 4. Reclassified maps of present and future total rainfall (in mm) during the MAM and OND seasons. The green colour shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (N) represents areas that are not suitable for green gram production in Kenya based on these classifications.

3.1.3. Overall Suitability of Green Gram Production in Kenya Obtained from a Weighted Overlay of Climate (Under Present and Future (RCP 4.5 and RCP 8.5 (2021 to 2050)), Soil and Altitude Parameters

This subsection presents the results of the green gram suitability maps. The suitability maps were obtained through the weighted overlay of climate, soil, and altitude parameters whose weights were obtained as shown in **Table 6**.

Figure 5 presents areas suitable for green gram production under historical climate data 1971-2000; **Figure 6** presents areas suitable for green gram production in the future under RCP 4.5 scenario for the years 2021 to 2050; **Figure 7** presents areas suitable for green gram production under future RCP 8.5 scenario for the years 2021 to 2050.

Figure 5 (historical), **Figure 6** (RCP 4.5), and **Figure 7** (RCP 8.5) show that most of the country is currently moderately suitable for green gram production during both the MAM and OND season, with highly suitable classes being found in Counties like Kitui, Machakos, and West Pokot among others.

Table 7 shows the area in km² suitable for green gram production during the MAM and OND season under baseline and future scenarios. While **Table 8** shows the percentage changes between the baseline and the future scenarios. The change in area suitability is only based on climatic parameters and not on the other conditions.

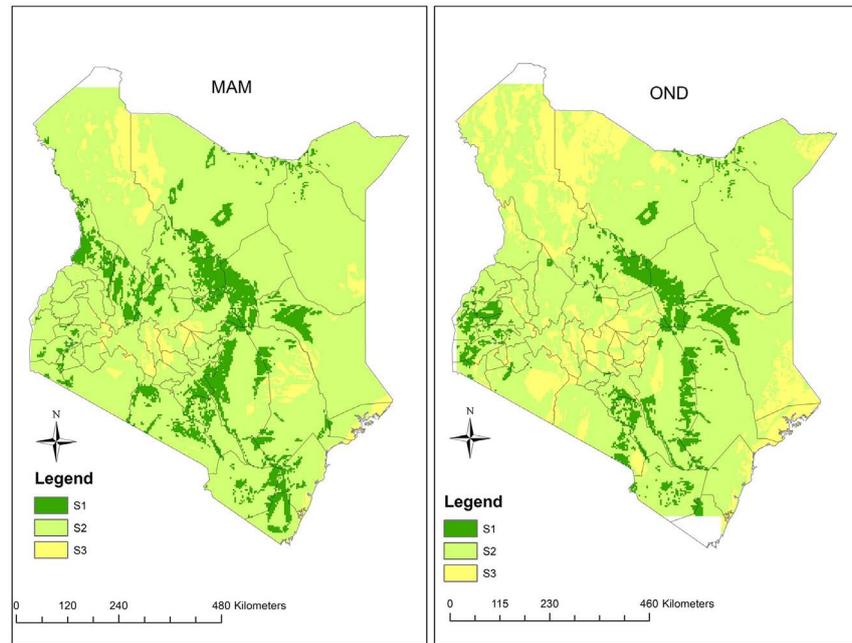


Figure 5. Present lands suitable for green gram production during the MAM and OND season. The green colour shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (N) represents areas that are not suitable for green gram production in Kenya based on these classifications.

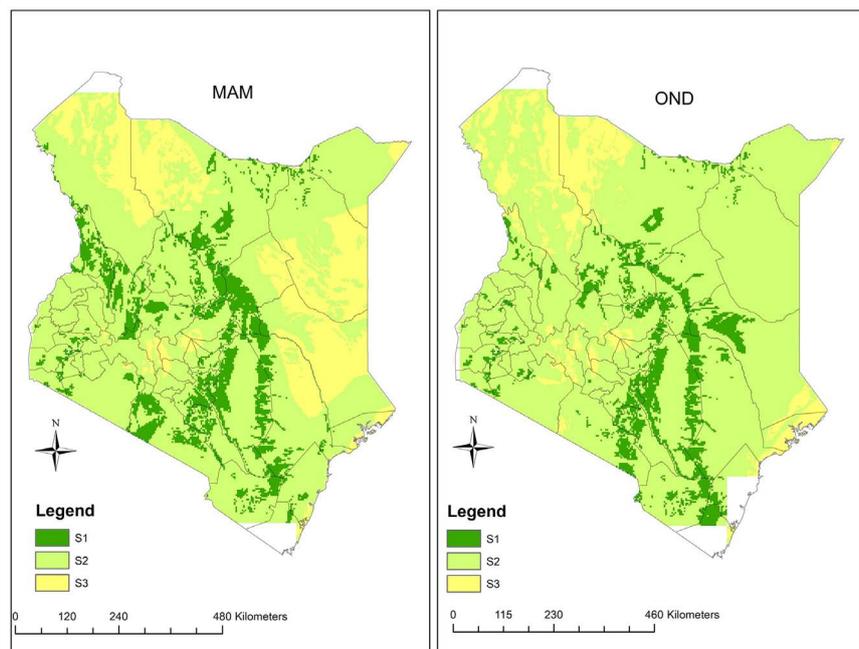


Figure 6. Future land suitable for green gram production during the MAM and OND season under the RCP 4.5 scenario for the years 2021 to 2050. The green shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (S4) represents areas that are not suitable for green gram production in Kenya based on these classifications.

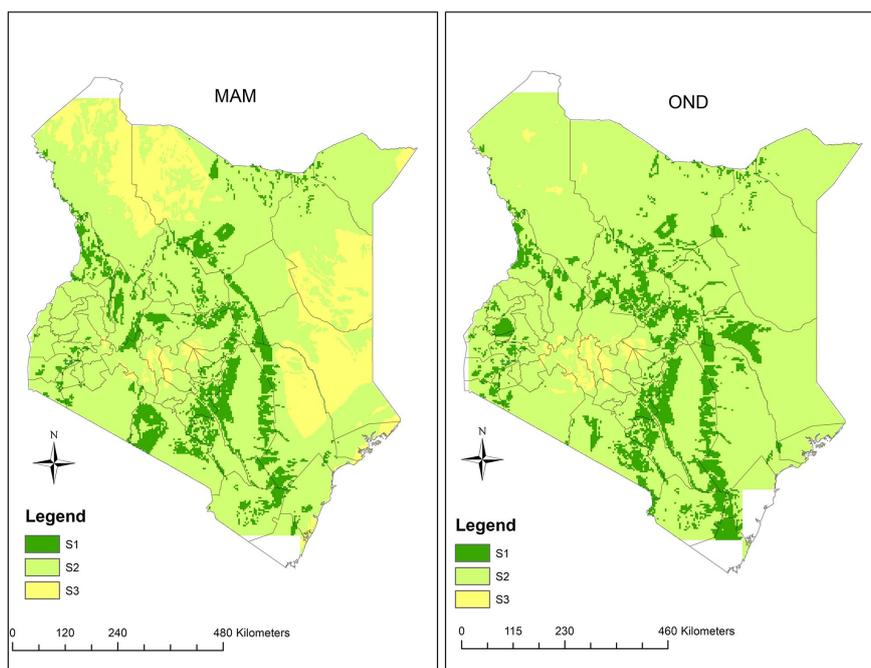


Figure 7. Future land suitable for green gram production during the MAM and OND season under the RCP 8.5 scenario for the years 2021 to 2050. The green colour shading (S1) represents the most suitable areas, light green shading (S2) represents the moderately suitable areas, yellow shading (S3) represents the marginally suitable areas, and red shading (N) represents areas that are not suitable for green gram production in Kenya based on these classifications.

Table 6. Weights obtained through the analytical hierarchy process showing how much each parameter contributes to the weighted overlay of green gram production.

	Rainfall	Temperature	Depth	Texture	CEC	pH	Drainage	Altitude	Weights	Rank
Rainfall	1	3.00	4.00	4.00	4.00	4.00	4.00	4.00	33.0%	1
Temperature	0.33	1	3.00	3.00	3.00	3.00	3.00	3.00	20.2%	2
Depth	0.25	0.33	1	2.00	0.50	0.50	0.50	2.00	6.5%	6
Texture	0.25	0.33	0.50	1	0.33	0.33	0.33	2.00	5.0%	7
CEC	0.25	0.33	2.00	3.00	1	1.00	0.50	2.00	9.0%	5
pH	0.25	0.33	2.00	3.00	1.00	1	0.50	3.00	9.5%	4
Drainage	0.25	0.33	2.00	3.00	2.00	2.00	1	3.00	12.4%	3
Altitude	0.25	0.33	0.50	0.50	0.5	0.33	0.33	1	4.3%	8

Table 7. Changes in land suitable for green gram production (in km²) under historical and future climate scenarios of RCP 4.5 and RCP 8.5 during the MAM and OND seasons.

	HISTORICAL		RCP 4.5		RCP 8.5	
	MAM (km ²)	OND (km ²)	MAM (km ²)	OND (km ²)	MAM (km ²)	OND (km ²)
S1	67,842.6	45,729.3	68,600.4	55,885.1	61,307.8	72,464.8
S2	470,972	423,463.3	391,768.9	457,128.1	404,721.1	488,043.8
S3	41,552.4	111,174.4	119,997.7	60,173.4	114,275.8	12,777.6

Table 8. Percentage changes in land suitable for green gram production between historical and future climate scenarios of RCP 4.5 and RCP 8.5 during the MAM and OND seasons.

	RCP 4.5		RCP 8.5	
	MAM	OND	MAM	OND
S1	1.1%	22.2%	-9.6%	58.5%
S2	-16.8%	7.9%	-14.1%	15.3%
S3	188.8%	-45.9%	175.0%	-88.5%

Currently, 67,842.62 km² and 45,729.3 km² are highly suitable for green gram production in Kenya during MAM and OND seasons respectively. The area highly suitable during MAM will increase slightly by 1.1% to 68,600.4 km² according to the RCP 4.5 and reduce by -9.6% to 61,307.8 km² under the RCP 8.5 scenario. The area highly suitable during OND will increase by 22.2% to 55,885.1 km² according to the RCP 4.5 and reduce by -9.6% to 72,464.8 km² under the RCP 8.5 scenario. This increase is as a result of favourable rainfall and temperature conditions in the future.

Currently, 470,972 km² and 423,463.3 km² are moderately suitable for green gram production in Kenya during MAM and OND seasons respectively. The area moderately suitable during MAM will reduce by -16.8% to 391,768.9 km² according to the RCP 4.5, and by -14.1% to 404,721.1 km² under the RCP 8.5 scenario. The area moderately suitable during OND will increase by 7.9% to 457,128.1 km² according to the RCP 4.5 and by 15.3% to 488,043.8 km² under the RCP 8.5 scenario.

Currently, 41,552.4 km² and 111,174.4 km² are marginally suitable for green gram production in Kenya during MAM and OND seasons respectively. The area marginally suitable during MAM will increase by 188.8% to 119,997.7 km² according to the RCP 4.5 and by 175.0% to 114,275.8 km² under the RCP 8.5 scenario. The area marginally suitable during OND will reduce by -45.9% to 60,173.4 km² under the RCP 4.5 and by -88.5% to 12,777.6 km² under the RCP 8.5 scenario.

4. Conclusions and Recommendations

This study sought to model green gram suitability in Kenya under changing climate. Maps showing different levels of green gram suitability in Kenya were obtained through a weighted overlay of climate characteristics (past and future rainfall and temperature), soil properties (depth, pH, texture, CEC, and drainage) and altitude parameters. The parameter maps were first classified into four classes: Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Not Suitable (N) in terms of their suitability for green gram production. The analyses showed that there are areas in Kenya that are currently not suitable for green gram production and these limitations prevent the successful sustained use of the land for green gram production. The maps of soil pH, depth, and drainage, and altitude show there are areas in Kenya that are currently not suitable.

When generating the suitability map for green gram production, the change in suitability was only attributed to climate parameters under past and future scenarios. Land use, physical and chemical properties of the soil, and topography were assumed to remain constant in the future since the model persists the prevailing structures.

The areas that are not suitable for green gram production in terms of the prevailing temperature under present conditions are counties of Nyeri and Nyandarua Counties; this is because these areas experience temperatures lower than 15°C. The areas in the northern and eastern parts of Kenya will not be suitable for green gram production in the future under both RCP 4.5 and RCP 8.5 scenarios during the MAM season since they will experience temperatures greater than 30°C which is not suitable for green gram production. A temperature range of 28°C to 30°C is considered optimum for seed germination and plant growth.

Rainfall areas that are not suitable for production are located in the north-western part of Kenya during the OND season for all scenarios, since rainfall amounts are less than 75 mm per season. No areas receive rainfall lower than 75 mm for all scenarios in the MAM season which would be unsuitable for green gram production. Water stress reduces the rate of uptake of nutrients, flowering, leaf area development, and photosynthesis causing yield reduction. An optimum rainfall of 250 - 350 mm is considered best for sustained germination.

Most of Kenya was found moderately suitable for green gram production during the MAM and OND seasons under the baseline, RCP 4.5 and RCP 8.5 scenarios. The area currently highly suitable for green production in Kenya will decrease during the MAM season but increase during the OND season for both RCP 4.5 and RCP 8.5 scenarios. In the highly suitable area for green gram production, players in the green gram value chain should take advantage of the good weather and adequately prepare since a good harvest is highly likely. Adequate preparation includes using the appropriate inputs in terms of seeds, pesticides, and fertilizers which will ensure positive results as the environment is already suitable for cultivation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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