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Modeling climate change impacts under future CCM3 scenario on sorghum (*Sorghum bicolor*) as an drought resilient crop in tropical arid Lombok Island, Indonesia

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Abstract. *Wibowo AA, Meylani V. 2024. Modeling climate change impacts under future CCM3 scenario on sorghum (*Sorghum bicolor*) as an drought resilient crop in tropical arid Lombok Island, Indonesia. Intl J Trop Drylands 8: 35-43.* The arid ecosystems and drought conditions exacerbated by climate change and rising CO_2 levels necessitate the identification of alternative drought-tolerant crops. *Sorghum bicolor* L. has emerged as a promising option due to its resilience to drought. However, there is dearth of information regarding its future potential distribution, particularly in arid regions like Lombok Island, Indonesia, where sorghum is being considered as a viable alternative to ensure food security. This study employs Maximum Entropy (MaxEnt) modeling, incorporating environmental and bioclimatic variables, along with the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) scenario reflecting doubled CO_2 levels, to model the future potential distribution of *S. bicolor*. The model projects a total suitable habitat area of 1,875 km^2, constituting 39.56% of Lombok Island's land area. Notably, very high-suitability areas of 175 km^2, and high-suitability areas of 200 km^2 encompass 3.69% and 4.22% of the island's territory, respectively, predominantly concentrated in the southern region of the island and characterized by low precipitation and high temperatures, particularly at altitudes ranging from 0 to 1,000 meters. The model's performance, evaluated using the Area Under the Curve (AUC), yields a score of 0.725, indicating a good level of accuracy. Key factors influencing sorghum distribution include annual precipitation (68.69%), isothermality (9.56%), temperature seasonality (9.56%), precipitation seasonality (8.69%), and annual mean temperature (3.47%). The CCM3 model forecasts an expansion of sorghum distribution toward the north, occupying approximately 6.25% of Lombok's total area. These findings highlight sorghum's adaptability and resilience to future climate changes, positioning it as a valuable resource for sustainable agriculture in arid environments.

Keywords: Arid, CCM3, El Nino, food security, MaxEnt

Abbreviations: MaxEnt: Maximum Entropy, NCAR: National Center for Atmospheric Research

INTRODUCTION

Lombok Island, situated in eastern Indonesia as part of the Lesser Sunda Island archipelago, is characterized by arid habitats and climates, predominantly consisting of shrublands and grasslands. The island's arid environment, exacerbated by the climate phenomena known like El Nino, has led to extensive dry seasons, threatening crop supplies, particularly rice. Approximately 8,400 hectares of rice fields on Lombok Island have been impacted by El Nino, highlighting the vulnerability of rice cultivation in such dry conditions (Yasin et al. 2004). Over the period from 1980 to 2020, Lombok Island experienced 13 extremely dry seasons (Yanti et al. 2022), accounting for 25.46% of all natural disasters and climate-extreme events. These dry spells lasting for four months on an average, have resulted in a significant decline in annual precipitation (1,900 mm from 2,702 mm), leading to famine situations (Akbar et al. 2021). In response to these challenges, *Sorghum bicolor* L., known for its drought-resilient properties, has emerged as a potential solution. Despite the low precipitation of 300 mm, sorghum requires only 350-400 mm of water annually Ruiz-Giralt et al. (2023), making it well suited for cultivation in arid environments (Zbigniew 2014). Sorghum also offer nutritional benefits, being rich in fiber and protein (McCann et al. 2015). However, it's worth noting that drought stress may impact sorghum's nitrogen uptake in the soil Sarshad et al. (2021).

To modeling the potential impacts of climate change, particularly increased CO_2 levels, the fourth iteration of the National Center for Atmospheric Research (NCAR's) Community Climate Model (CCM), namely CCM3, has been utilized. This model simulates a twofold increment of CO_2 concentration in the atmosphere, providing insights into future climate scenarios (Chen et al. 2003). For modeling species distribution and habitat suitability, various approaches exist, including statistical liner models like Generalized Additive Model (GAM) and the Generalized Linear Model (GLM), geographical analysis-based models such as domain and biomapper, and more recent Maximum Entropy (MaxEnt), in particular, offers several advantages in terms of capacity, data requirements, accuracy, and the ability to discriminate environmental variables (Marcer et al. 2013; Stephenson et al. 2022).

In Indonesia, sorghum has been considered a substitute rice (Paesal et al. 2021), and the Government of Indonesia has planned allocation of 115,000 ha of land for sorghum farming in 2023 and an additional 154,000 ha in 2024. However, there is still limited information on the potential distribution of sorghum under the CCM3 climate change model, especially on Lombok Island. Hence, this study aims to identify potential sorghum farming areas on Lombok Island using MaxEnt modeling. The results of this study are expected to contribute to food security in arid environment of Lombok Island.

MATERIALS AND METHODS

Study area

This study was conducted on Lombok Island (115.816605°-116.609078° E and 8.085101°-8.972345° S), located in West Nusa Tenggara Province, Indonesia (Figure 1). This island is part of the Lesser Sunda Islands, separated from Bali to the west by the Lombok Strait and from Sumbawa to the east by Alas Strait. Lombok Island comprises of four districts, namely West Lombok, Central Lombok, East Lombok, North Lombok, along with Mataram City. This island has a total area of 5,435 km^2. Positioned amidst the seas, Lombok Island is bordered by the Bali Sea to the north and the Timor Sea to the south. .

Mount Rinjani, a stratovolcano and the second-highest volcano in Indonesia at 3,726 meters (12,224 ft), is situated at the island's center, rendering Lombok the 8th-highest island in the country. The ecosystems of Lombok Island exhibit dominance by patchy and fragmented savanna and grassland ecosystems, alongside lowland tropical rain forests, upland tropical forests, and sub-alpine vegetation, owing to the dry temperature and arid ecosystems. Additionally, the island features numerous meadows and shrublands (Sapta et al. 2015).

Areas of southern Lombok Island are designated as arid ecosystems and are vulnerable to water shortages due to inadequate rainfall and a scarcity of water sources. In October, the maximum air temperature ranges from 33.4°C to 35.8°C, while the lowest air temperature ranges from 20.6°C to 21.7°C. Humidity in West Nusa Tenggara Province fluctuates between 68% and 88%, with average wind speeds ranging from 2.30 to 5.30 knots and maximum wind speeds reaching 5 knots. During dry seasons, annual rainfall rates may drop as low as 1,900 mm.

Procedures

Sorghum occurrence surveys

The study methodology followed the methods developed by Semu et al. (2021), including species occurrence, environmental variables, and model evaluation. To document the presence of sorghum in real time, field surveys and explorations were carried out across Lombok Island from September to October 2023. In September, surveys were conducted in North Lombok, Timur and Tengah, while in October, West Lombok and Mataram City were surveyed. Information retrieved from The Herbarium Bogoriense, Indonesia, a database developed from literature reviews, and the Agency for Agriculture and Forestry of the Ministry for Agriculture and Forestry, Indonesia, were used to identify sorghum during field surveys. The Global Positioning System (GPS) of the Garmin Etrex 30 was used to capture the geographic coordinates of *S. bicolor* presences in the field. Subsequently, the data were transformed into Microsoft Excel and exported in CSV format for utilization in MaxEnt habitat suitability modeling.

Environmental variables

A variety of environmental parameters were included in this study (Table 1), including the most important bioclimatic variables identified by Dong et al. (2023) and Arshad et al. (2022). These variables consist of the yearly mean temperature (°C), yearly precipitation (mm), isothermality (%), temperature seasonality, and precipitation seasonality. Bioclimatic variables from the WorldClim global climate database (www.worldclim.org, version 2.1) have been extensively used in habitat suitability modeling in the Asian region (Pradhan and Setyawan 2021). Additionally, geophysical information in the form of altitude and topography was obtained through the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 30 meters.

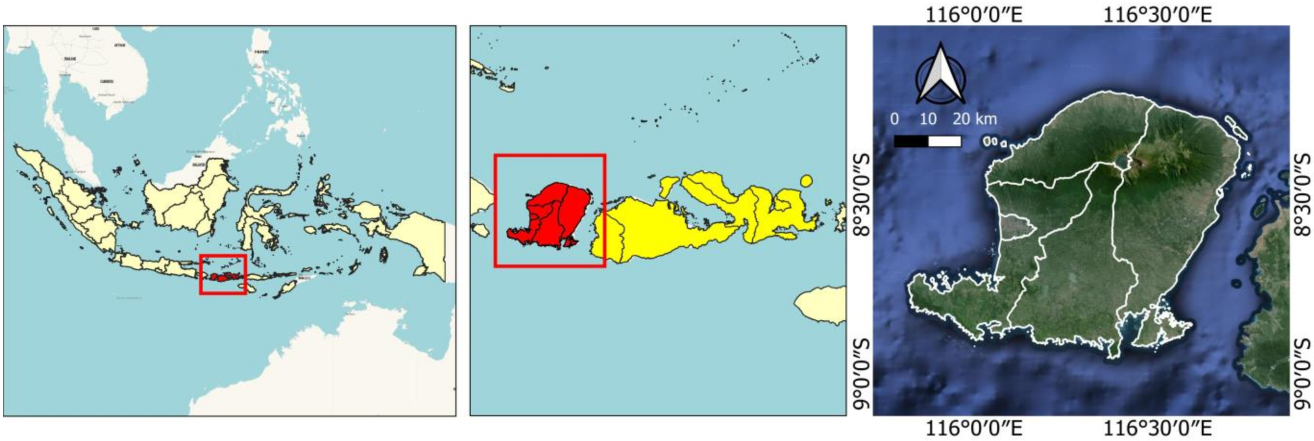

Figure 1. Location map of the study area in Lombok Island, West Nusa Tenggara Province, Lesser Sunda Island archipelago, Indonesia

Table 1. Environmental variables used in this study

Variables	Sources	Format	Unit
Annual mean temperature	www.worldclim.org	Image data in Raster	°C
Isothermality	www.worldclim.org	Image data in Raster	%
Annual precipitation	www.worldclim.org	Image data in Raster	mm
Temperature seasonality	www.worldclim.org	Image data in Raster	dimensionless
Precipitation seasonality	www.worldclim.org	Image data in Raster	dimensionless
Topography and altitude	30 m SRTM	Image data in Raster	m
Current climate	www.worldclim.org	Image data in Raster	°C
Future climate CCM3 $2\times CO_2$	www.worldclim.org	Image data in Raster	°C

To produce an accurate and informative habitat suitability model, these environmental variables were selected based on their significant influence. The contribution of each environmental variable to the final model of sorghum distribution was assessed using Jackknife analysis. Two crucial elements for comprehending and quantifying the environmental variable's contribution and significance to the MaxEnt model were the contribution percentage and permutation. Some environmental variables were not employed in the model creation due to their negligible contribution. These variables exhibited an average contribution percentage of less than 6%, or a modest permutation relevance of less than 6%.

Suitability analysis

MaxEnt analysis was utilized to generate projected suitability maps of *S. bicolor* throughout Lombok Island. Suitability analysis was carried out utilizing the MaxEnt tool incorporated in dismo package within R platform version 3.6.3 (Mao et al. 2022), along with relevant R packages required for mapping viz. maptools, rgdal, raster, and sp (Lemenkova 2020), and the BioClim module inside the DIVA-GIS platform (Xie et al. 2020). The input environmental variables for MaxEnt included mean annual temperature, annual precipitation, isothermality, seasonality of temperature and precipitation.

The contribution and influence of each environmental variable on the *S. bicolor* habitat suitability model were ascertained within the model through a Jackknife test. The receiving operating curve (AUC) area was utilized to evaluate performance of the model. AUC serves a versatile independent threshold statistic, capable of assessing how effectively a model can differentiate between the presence and absence of a species to determine its potential distribution. According to Zhu et al. (2017), the range of AUC values spans from 0, considered least suitable, to 1. A value nearing 1 indicates that the final model is very effective, informative and more accurate, while a value below 0.5 suggests that that the real-world species occurrence is uncommon and the model provides no more utility than random and unrevealing data. Wei et al. (2018) delineate five different habitat appropriateness levels on the MaxEnt model suitablity map: 0 for inappropriate, 1 for suitability at a moderate level, 2 for suitability at a medium level, 3 for suitability at a high level, and 4 for suitability at a very high level. The analytical outcomes from the MaxEnt models predicting the suitability ranges for *S. bicolor* were subsequently imported into GIS for further examination and visualization.

Model evaluation

The model evaluation in this study follows the approach outlined by Reddy et al. (2015) and Song et al. (2023). Area Under the Curve (AUC) analysis was employed to evaluate the model, with the MaxEnt model used to determine the percentage contribution of each variable to the species distribution. Each variable's contribution to the species' distribution is represented by the percentage contribution. The Area Under the Curve (AUC), combined with the Receiver Operating Characteristic (ROC) curve, was used to evaluate the accuracy of the model's predictions. The variables for the MaxEnt model were selected following Zhao et al. (2018). Jackknife was used to methodically eliminate every variable and assess the most important topography and bioclimatic environmental variables. Jackknife test enable the identification of the most influential variables to ascertain the potential species distribution. The response curve generated by the model indicates the relationship between topographic and bioclimatic variables and the potential habitat for the species. The proportional percentage contributions of each environmental variable to the MaxEnt model were computed accordingly.

CCM3 model

This study employed two models. The first utilized the MaxEnt model with the dismo package in R to predict the current potential distribution of sorghum. The second model employed CCM3 model with the BioClim module of DIVA-GIS to project both the current and future potential sorghum under doubled CO_2 conditions. The variables used to develop the current and future potential distribution of sorghum under BioClim model (Table 1) included current climate data with 10 minute resolution and future climate data under the CCM3 $2\times CO_2$ scenario, also with a 10-minute resolution (Govindasamy et al. 2003).

RESULTS AND DISCUSSION

Sorghum occurrences

According to the collected occurrence data and survey from September to October 2023, *S. bicolor* was predominantly observed (Figure 2) within the 116°-116.5° E and 7.5°-8° S in the northern coasts of island and between 116°-116.5° E and 8.5°-9° S in the southern coasts of island (Table 2). A total of nine instances of sorghum sightings were recorded. Across Lombok Island, sorghums were predominantly found in low-lying areas with altitudes ranging from 0-500 m. Notably, sorghum occurrence were not found in high-altitude regions exceeding 500 m, primarily within the hilly terrain in the northern part of the island. Furthermore, during our ground field surveys, no evidence of sorghum presence was found in the western part or in West Lombok Districts.

Model evaluation and validation

The reliability of modeling outcomes was evaluated and validated, with the area under the Receiver Operating Characteristic (ROC) curve (AUC), serving as a key metric. In this study, the AUC value for the MaxEnt model was 0.725 under the current conditions (Figure 3). This indicates that the MaxEnt model exhibited good predictive performance regarding the potential distribution of sorghum on Lombok Island.

Environmental variable distributions

Spatial distributions of environmental variables across Lombok Island, consisting of mean annual temperature, annual precipitation, isothermality, seasonality of temperature, and precipitation are depicted in Figure 4. Analysis reveals that the annual mean temperature tends to be lower in the northern regions, particularly at high altitudes. While, lower altitudes in the southern areas exhibit higher annual mean temperature alongside reduced precipitation. In contrast, the northern regions, characterized by lower temperatures, experience higher annual precipitation rates and greater precipitation seasonality. Additionally, a peak in isothermality was observed in the northern parts of the island.

Environmental variable contributions

Table 3 presents the results of Jackknife testing on the % contribution and permutational importance of predictor variables. Notably, the most influential variables, ranked from highest to the lowest contribution, include annual precipitation (68.69%), isothermality (9.56%), temperature seasonality (9.56%), precipitation seasonality (8.69%), and annual mean temperature (3.47%) These finding affirmed that annual precipitation, followed by either isothermality or temperature seasonality, were the most relevant variables for predicting potential habitat suitability for sorghum in the study area.

Table 2. The coordinates of occurrence points of sorghum collected from ground field surveys

Occurrence Points	Longitude	Latitude	Districts	Sources of Occurrence Points from Ground Surveys
1	116.258343°	-8.735645°	Lombok Tengah	September 2023
2	116.077362°	-8.569429°	Mataram City	October 2023
3	116.282666°	-8.739216°	Lombok Tengah	September 2023
4	116.198577°	-8.313063°	North Lombok	September 2023
5	116.439969°	-8.291627°	North Lombok	September 2023
6	116.272605°	-8.288367°	North Lombok	September 2023
7	116.651439°	-8.515896°	East Lombok	September 2023
8	116.486992°	-8.756678°	East Lombok	September 2023
9	116.477366°	-8.882698°	East Lombok	September 2023

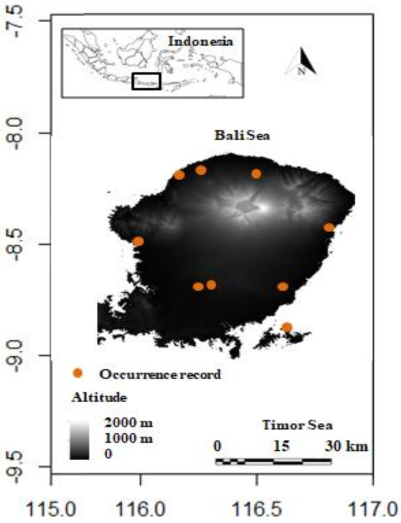

Figure 2. Current occurrences of *Sorghum bicolor* across Lombok Island in various altitudes based on ground field surveys

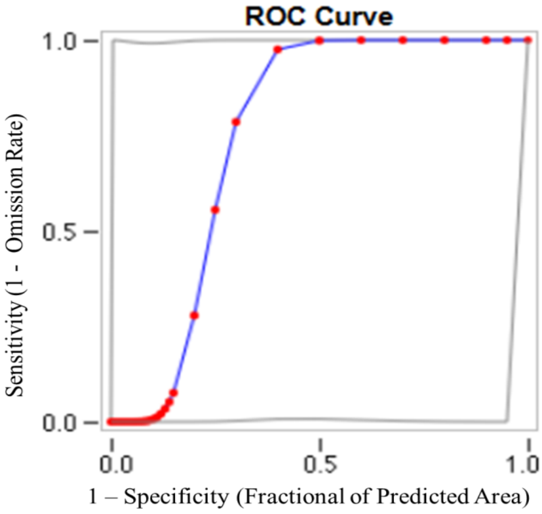

Figure 3. The Receiver Operating Characteristic (ROC) curve result of the MaxEnt modelling

Table 3. Relative contributions of the environmental variables to the MaxEnt.

Environmental Variables	Relative Contribution (%)
Annual mean temperature	3.47
Isothermality	9.56
Annual precipitation	68.69
Temperature seasonality	9.56
Precipitation seasonality	8.69

Response curves of environmental variables

The response curves depicted in Figure 5 illustrate the relationships between the probability of occurrence and the habitat suitability level of sorghum with each environmental variable. Notably, the species response curve delineates a negative relationship with several environmental variables, including annual precipitation, isothermality, temperature seasonality, and precipitation seasonality. While, the annual mean temperature was the only variable showing positive relationships. These response curves underline the considerable influence of these environmental variables on the distribution of sorghum across Lombok Island. Specifically, the suitability level for growth increases with rising temperature, ideally ranging between 24 to 25°C or higher. Similarly, the suitability level for growth increases as precipitation and isothermality decrease, ideally aligning with areas with annual precipitation of less than 1,000 mm. This relationship shows the preference for and adaptation of sorghum to the arid ecosystems characterized by drought conditions.

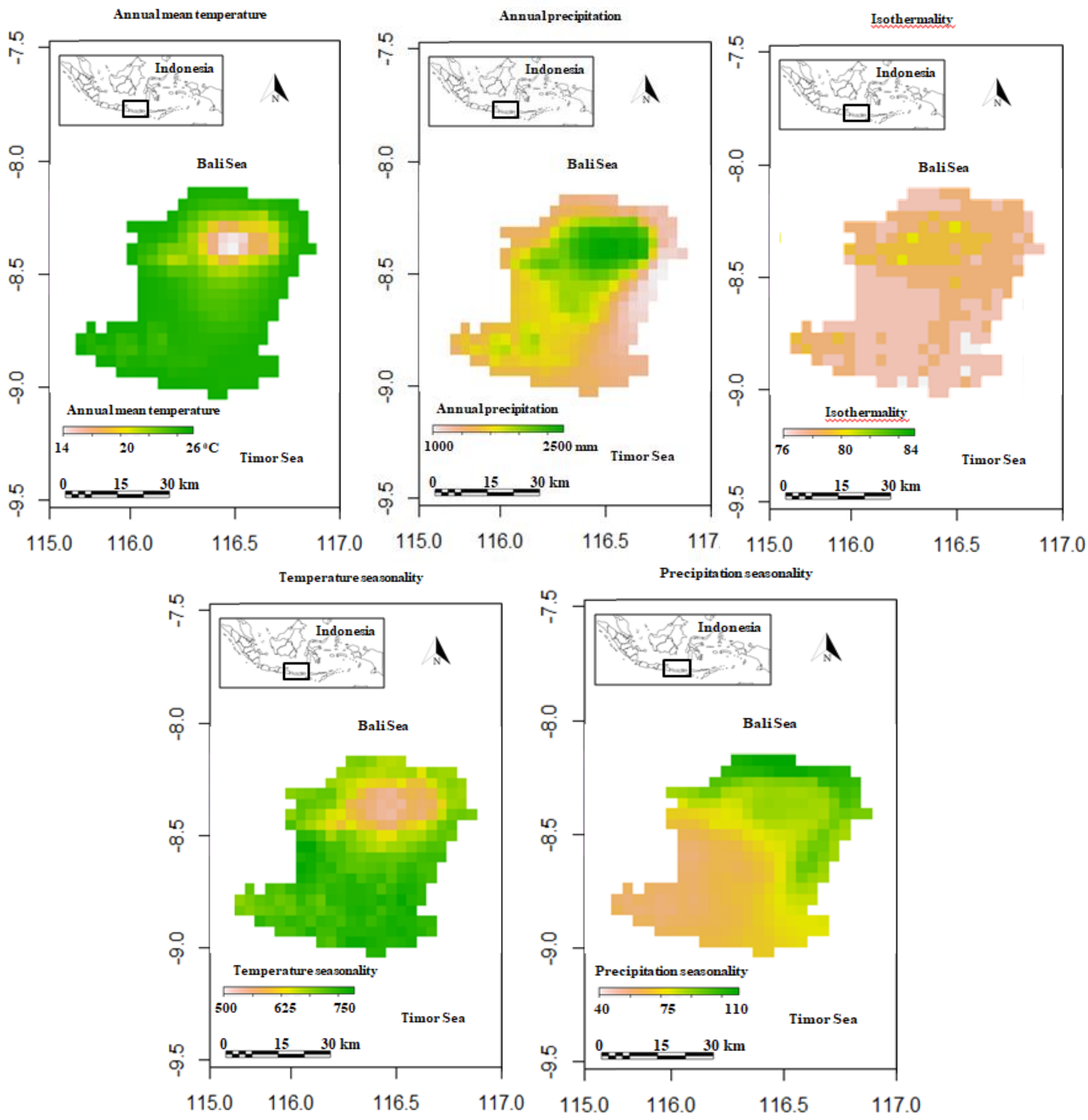

Figure 4. Distributions of environmental variables including annual mean temperature (°C), annual precipitation (mm), isothermality (%),temperature seasonality (dimensionless), and precipitation seasonality (dimensionless) in Lombok Island, Indonesia

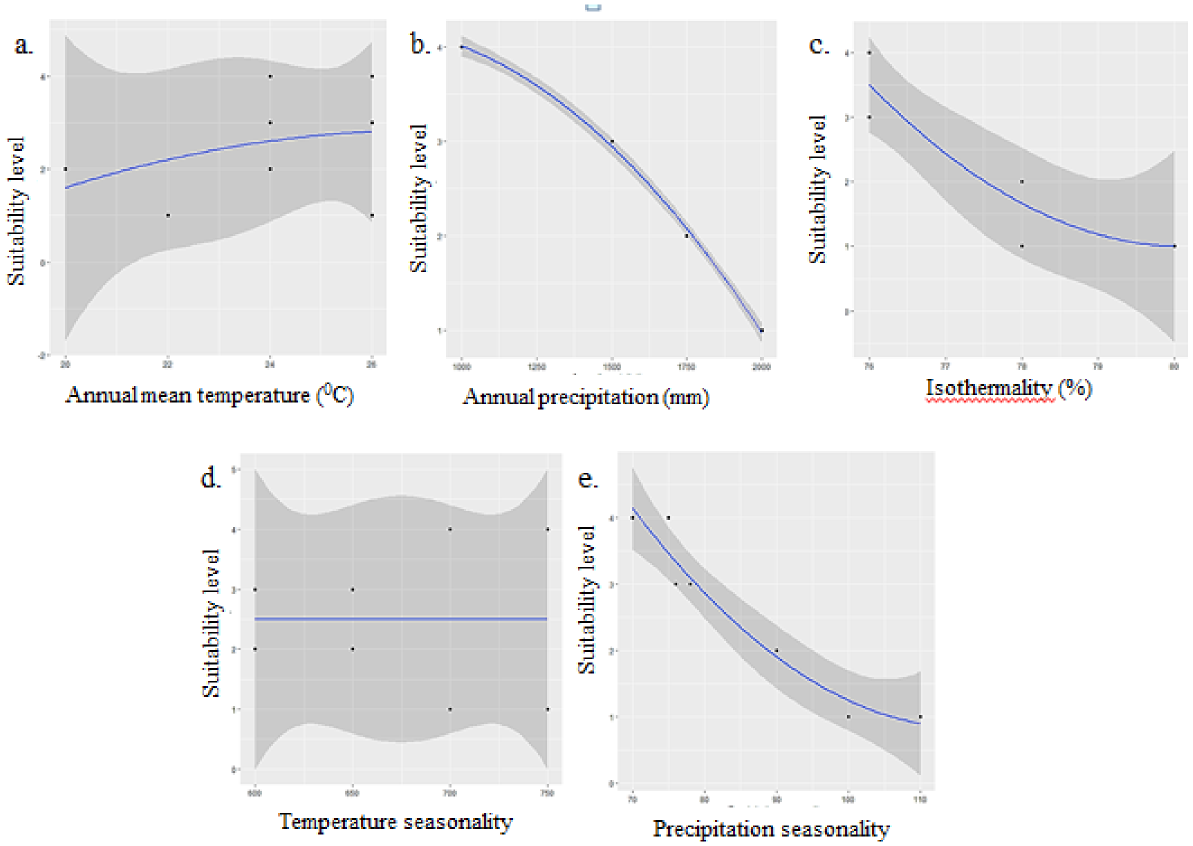

Figure 5. The response curves with 95% CI (shaded area)for the contributing variables for sorghum habitat suitability levels including (a) annual mean temperature (°C), (b) annual precipitation (mm), (c) isothermality (%),(d) temperature seasonality (dimensionless), and (e) precipitation seasonality (dimensionless) in Lombok Island, Indonesia

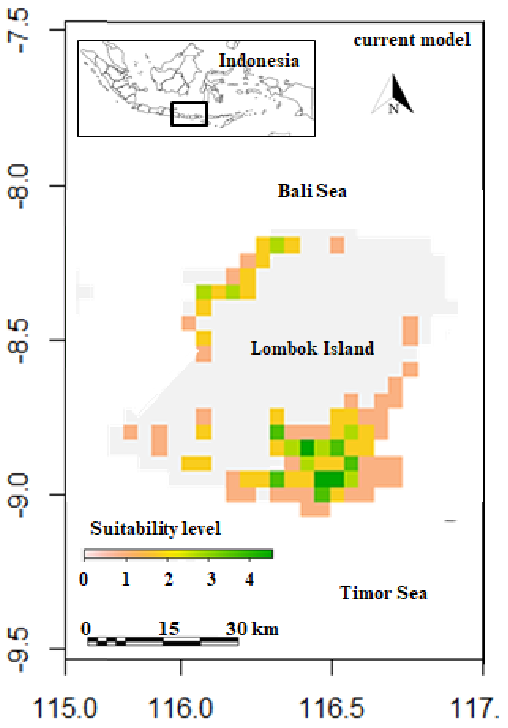

Figure 6. Distribution of current potential suitable areas for sorghum on the Lombok Island, Indonesia based on MaxEnt (Suitability level 0: unsuitable,1: low suitability, 2: medium suitability, 3: high suitability, 4: very high suitability)

Current suitability model

The current suitability model for sorghum, using MaxEnt model based on R dismo package, was classified, mapped, and evaluated to calculate the land area for each identified suitable habitat (Figure 6). Suitable habitats for sorghum on Lombok Island were predominantly located in the northern and southern regions, primarily in the low-lying areas with altitudes ranging of 0-1,000 m. Conversely, the northern parts, characterized by elevations exceeding 1,000 m and predominantly highlands, lacked suitable areas for sorghum cultivation. The total potential suitable habitat for sorghum, as projected by the MaxEnt modeling, was estimated at around 1,875 km^2 or equivalent to 39.56% of Lombok Island's total area (Table 4). This estimation includes around 175 km^2 of land classified as very highly suitable (3.69%), 200 km^2 as highly suitable (4.22%), 625 km^2 as moderately suitable (13.18%), and 875 km^2 as least suitable (18.46%) on Lombok Island.

Table 4. Predicted suitable area in km^2 for *Sorghum bicolor* habitat suitability in Lombok Island, Indonesia based on MaxEnt

Suitability Levels	Area in km^2	% of Lombok Island's Total Area
Low suitability	875	18.46
Medium suitability	625	13.18
High suitability	200	4.22
Very high suitability	175	3.69
Total	1,875	39.56

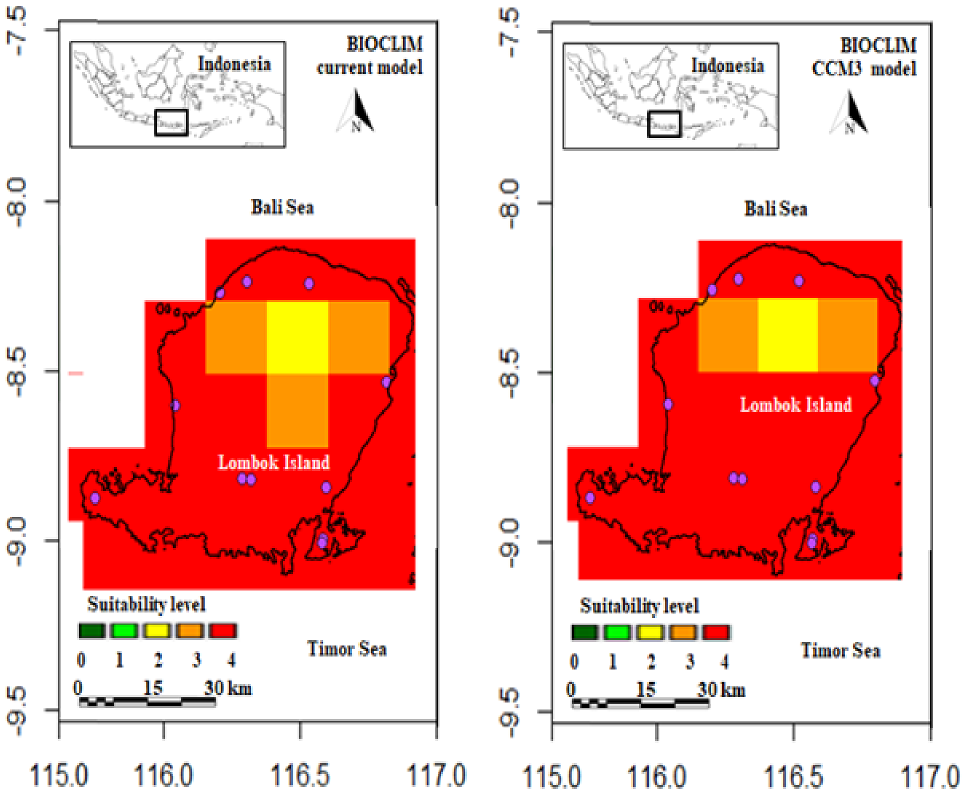

Figure 7. Distribution of current (left) and future (right) potential suitable areas for sorghum on the Lombok Island, Indonesia under CCM3 scenario based on BioClim (Suitability level 0: unsuitable,1: low suitability, 2: medium suitability, 3: high suitability, 4: very high suitability)

Future CCM3 suitability model

The impact of climate change on suitable areas for sorghum was modeled using CCM3 based on DIVA-GIS BioClim module, assuming a near doubling of CO_2 levels (Figure 7). The model reveals a northward expansions of sorghum habitats in response to elevated CO_2 concentrations and temperature. Approximately 6.25% of Lombok's total land area, previously unsuitable for sorghum cultivation in the northern regions, are now deemed suitable. This indicates that climate change may promote the presence and distribution of sorghum on the island.

Discussion

Given sorghum's drought tolerance, it's expected to be particularly sensitive to changes in the climate and precipitation. This study aimed to predict how various climate variables would affect sorghum as a potential crop. This is the first study to explore sorghum range expansions using the MaxEnt species distribution model, particularly in the Southeast Asia. Carefully selected occurrence data for sorghum and relevant environmental variables were validated to ensure model accuracy. The AUC was used to optimize and evaluate model parameters for sorghum, revealing good prediction accuracy. These findings align earlier investigations (Table 5). While, sorghum's potential distribution has been modeled in China, India, and Africa, information remained scarce in the Southeast Asia region.

Sorghum distributions on Lombok Island was found to be influenced primarily by precipitation, exhibiting a negative correlation, while demonstrating resilience to temperature increases. Mugiyo et al. (2022) emphasized the significant impact of rainfall-related parameters, particularly precipitation, on sorghum's potential applicability. Sorghum's characteristic drought tolerance, as highlighted by Niu et al. (2022), emphasizes its ability to withstand varying climatic conditions. The study revealed that environmental variables such as temperature and precipitation collectively contributed 86.2% to the model, indicating sorghum heat resistance and preference for locations with higher temperatures and humidity.

Table 5. Comparisons of sorghum MaxEnt studies in other locations

Locations	AUC	% High Suitable Areas	References
KwaZulu-Natal, South Africa	0.93	13.4	Mugiyo et al. (2022)
China	0.881	na	Niu et al. (2022)
Telangana state, India	na	na	Natarajan et al. (2016)
Kenya, Africa	0.97	na	Kigen et al. (2014)
Lombok island, Indonesia	0.725	3.69-4.22	This study

Temperature seasonality and isothermality were identified as influential factors alongside precipitation variables in this study. This is in line with the findings of Huang et al. (2021), suggesting that plant groups tend to thrive in flat topographies characterized by higher temperature variability, isothermality, and seasonality. Sorghum's potential habitat was estimated to be highly suitable in flat lowlands with elevations below 1,000 m on Lombok Island.

The resilience and adaptation of sorghum to low precipitation are attributed to its physiological and phonological characteristics. During the flowering stage, most plants experience reduced chlorophyll levels, increasing their vulnerability to drought. However, sorghum exhibits an opposite response, producing more chlorophyll to mitigate drought threats (Prasad et al. 2021). The physiological adaptation of sorghum to drought begins at the germination stage, where it delays germination to enhance osmotic potential and reduce water uptake during prolonged dry periods (Abreha et al. 2022). Sorghum is a C4 plant that has evolved to grow at environment above 20°C (Basu et al. 2016), and it has the ability to regulate stomatal closure while sustaining photosynthesis, crucial for minimizing water loss and adapting to arid environments (Rutayisire et al. 2021), which explains the predicted expansion of sorghum to the south of Lombok Island.

Compared to other studies, the percentage of suitable areas identified in this study is relatively low, attributed to Lombok Island's diverse topography and altitudinal variations, which have corresponding effect on the climatic variables, constraining potential spread of sorghum. For instance, the northern parts of Lombok Island, characterized by highlands characterized with high precipitation and low temperatures, are less conducive to sorghum growth.

The study forecasts an expansion of sorghum's suitable habitats to the north of Lombok Island in the future, driven by climate change. However, presence of sorghum still faces threats from non-climatic factors and rising CO_2 levels, including anthropogenic activities (Gafna et al. 2017), livestock grazing (Mahmoudi 2012), and invasive plant species (Čuda et al. 2015; Iqbal et al. 2020). Hence, future modeling efforts should consider these issues to model sorghum's suitable habitats.

The utlilization of maximum entropy model in this study provides insights into sorghum's spatial distribution and habitat suitability on arid Lombok Island. The results and species distribution model serve as valuable resources for devising future strategies to understand the impact of climate variables on sorghum's potential distributions in this region. The study illustrates how farmers and agriculture planners can leverage MaxEnt modeling approaches to identify areas where sorghum cultivation practices yield optimal outcomes. This emphasizes the importance of prioritizing areas to maintain sorghum's natural geographical distribution and ensure food security, primarily on the arid Lombok Island. Key environmental variables affecting sorghum distribution on the arid Lombok Island were identified as annual precipitation, isothermality, temperature seasonality, precipitation seasonality, and annual mean temperature, contributing to 68.69%, 9.56%, 9.56%, 8.69%, and 3.47% of the effects, respectively. The total suitable distribution region of sorghum on arid Lombok Island accounted for 39.56% of the island's total land area, with very high-suitability areas covering 175 km^2 (3.69%) and high-suitability areas covering 200 km^2 (4.22%), primarily concentrated in the southern parts of the island at altitudes of 0-1,000 m and characterized by low precipitation and high temperature.

Furthermore, the CCM3 model, accounting for double CO_2 concentrations, suggests that sorghum-suitable areas would expand northward in the future, with no significant changes observed in the current suitable areas. This resilience to climate change highlights sorghum's adaptability and ability to counter environmental challenges.

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