

Enhancing the resilience of fonio, a neglected crop in Togo, to climate change

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Summary : Despite its recognized nutritional and therapeutic properties, fonio (*Digitaria exilis* Stapf.) remains a neglected crop in Togo. Its production has decreased significantly in recent years due to the effects of climate change. This study is intended to help improve the resilience of fonio growing in Togo to climate change. In particular, the study aims to: (i) identify potential fonio growing areas in Togo, (ii) assess the impact of climate change on the distribution of fonio growing areas up to 2055, and (iii) identify priority fonio growing areas in the context of climate change in Togo. The MaxEnt algorithm was used to estimate the current and future potential distribution area (by 2055) according to the SSP 126 and 585 scenarios using fonio cultivation areas or points of presence and climate data. Zonation software was used to rank priority habitats. The variables that contributed most to the construction of the distribution models for areas suitable for fonio cultivation were the annual temperature range, temperature seasonality, mean monthly diurnal variation and annual rainfall. Approximately 63.69% of the national territory is currently considered very suitable for growing fonio. By 2055, the very favourable areas are projected to decrease by 2.57% in the SSP 126 scenario and by 3.13% in the SSP 585 scenario. To improve the resilience of the crop and make fonio production in Togo sustainable, ecological zones I, II and IV should be prioritized in policies to promote fonio cultivation.

Key words : Fonio, growing areas, climate change, sustainable production, Togo.

Résumé : Le fonio (*Digitaria exilis* Stapf.) reste une culture négligée au Togo, bien que ses vertus alimentaires et thérapeutiques soient reconnues. Sa production a considérablement régressé ces dernières années sous les effets des changements climatiques. Cette étude vise à contribuer à l'amélioration de la résilience de la culture du fonio face aux effets des changements climatiques au Togo. Il consiste plus précisément à : (i) identifier les habitats potentiels de culture du fonio au Togo, (ii) évaluer l'impact des changements climatiques sur la distribution de l'aire de culture du fonio à l'horizon 2055 et (iii) déterminer les aires prioritaires de culture du fonio dans le contexte des changements climatiques au Togo. Les zones de culture et les points de présence du fonio couplés aux données climatiques ont été utilisées pour estimer l'aire de distribution potentielle actuelle et future (à l'horizon 2055) suivant les scénarios SSP 126 et 585 à partir de l'algorithme MaXent. La hiérarchisation des habitats prioritaires a été réalisée avec le logiciel Zonation. La plage de la température annuelle, la saisonnalité de température, la moyenne mensuelle des variations journalières et la précipitation annuelle sont les variables ayant contribué le plus à la construction des modèles de distribution des aires favorables à la culture du fonio. Environ 63,69 % du territoire national est actuellement très favorable à la culture du fonio. Une réduction de 2,57 % sous le scénario SSP 126 et 3,13 % suivant le scénario SSP 585 des zones très favorables est prédite à l'horizon 2055. Les zones écologiques I, II et IV devraient être priorisées dans les politiques de la promotion de la culture du fonio pour améliorer la résilience de la culture et rendre durable la production du fonio au Togo.

Mots clés : Fonio, aires de cultures, changement climatique, production durable, Togo.

INTRODUCTION

Fonio (*Digitaria exilis* Stapf.), a species of millet that has been neglected due to the small size of its grains, is experiencing renewed interest from consumers who recognize its taste and nutritional qualities. It is distinguished by its elevated concentrations of iron, magnesium, zinc, manganese, thiamine (vitamin B1), riboflavin (vitamin B2), calcium, and phosphorus, surpassing those of other cereals (MAEDR, 2023). It also contains twice as many essential

amino acids for humans as other cereals (MAEDR, 2023). Its high content of essential amino acids (methionine and cysteine) and fibre makes it highly recommended for pregnant women and diabetics, as it has a relatively low glycaemic index (around 66 compared to 95 for rice) (Traore *et al.*, 2009 ; Cruz et Béavogui, 2011). Fonio generates significant financial income for farmers, particularly women, who are traditionally involved in processing and marketing (Paraïso *et al.*, 2011 ; Diop *et al.*, 2018). This neglected and underutilized food

crop is crucial for food security and combatting poverty, particularly among rural populations (Kanlindogbe *et al.*, 2020).

Fonio can be cultivated in a wide range of environmental conditions (Dièye, 2022). It is a drought-tolerant plant that thrives in nutrient-poor sandy soils (Adoukonou-Sagbadja *et al.*, 2010) and can withstand climatic hazards (Cruz *et al.*, 2004). It exhibits enhanced resilience to aridity, a trait attributable to its C4 metabolism, while concurrently contributing to the preservation of the ecosystem through the provision of optimal vegetative cover on ecologically vulnerable and underappreciated soils (Niaone *et al.*, 2021). However, these qualities are not immune to the effects of climate change. It is therefore necessary to anticipate the impact of climatic factors on the fonio habitat. This will enable decision makers to develop consistent conservation and improvement strategies (Avaligbé *et al.*, 2021).

This study is guided by three questions. What are the current and future potential areas for fonio cultivation in Togo? What impact is likely to be had by climate change on these distribution areas? Which areas should be prioritized for fonio cultivation in Togo? This study aims to contribute to the sustainable production of fonio in the context of climate change in Togo.

More specifically, the study aims to: (i) identify current and future potential habitats for fonio cultivation in Togo; (ii) assess the impact of climate change on the distribution of fonio cultivation areas by 2055; and (iii) determine priority areas for fonio cultivation in Togo.

MATERIAL AND METHODS

1. Description of the study area

Togo is a country in West Africa located on the shores of the Gulf of Guinea. The area covered is 56,600 km² and the latitude extends from 6° to 11° N and the longitude from 0° to 1°5' E. The country is divided into five economic and administrative regions. Its terrain is divided into two main areas: one mountainous and the other flat. The mountainous area consists mainly of the Atakora Range, locally known as the Togolese Mountains, and runs from south-west to north-east across the country in a scarf-like shape. Plains lie on either side of these mountains, the most important of which are the Mono River Basin in the south and the Oti River Basin in the north (Addra *et al.*, 1994). The climate is fairly mild in the intertropical zone, but varies significantly from south to north (Bup *et al.*, 2014). This divides the country into two climatic zones, with the boundary

located at the latitude of Blitta. The north has a Sudanese climate, consisting of a single rainy season and a dry season. The duration of these seasons varies slightly from year to year. Annual rainfall ranges from 800 to 1,400 mm distributed across two rainy seasons. The average annual temperature is 27°C. The southern part of the country has a Guinean climate characterized by two dry and two rainy seasons. Annual rainfall in this region fluctuates between 1,400 and 1,500 mm, with an average annual temperature of 26.5 °C.

Togo is mainly covered by savannahs (Brunel *et al.*, 1984) and subdivided into five (5) ecological zones defined according to relief and floristic specificity (Ern, 1979). Zone I, also known as the north-eastern plains zone, was originally covered by Sudanese savannahs (Brunel *et al.*, 1984). This area is characterized by vast agroforestry parks dominated by Shea, African locust bean, roast, baobab and tamarind trees (Padakale *et al.*, 2015; Folega *et al.*, 2019 ; Samarou *et al.*, 2021 ; Atakpama *et al.*, 2022b). Zone II, the northern mountain zone, comprises open forests, dense dry forests and savannahs (Dourma *et al.*, 2012). This area is home to large parklands of the baobab, the African locust bean and Shea butter trees (Wala *et al.*, 2009 ; Padakale *et al.*, 2015). Zone III, the central plains, is characterized mainly by open forests, dense dry forests, and Guinean wooded

savannahs (Atsri *et al.*, 2018 ; Djideal *et al.*, 2024). Zone IV constitutes the southern part of the Togolese Mountains and is home to some of Togo's densest semi-deciduous forests (Akpagana, 1989). These native formations are almost completely degraded (Kombate *et al.*, 2019 ; Hlovor *et al.*, 2021). They have been transformed into agroforests of coffee, cocoa and fruit trees (Koda *et al.*, 2016 ; Djiwa *et al.*, 2020). The large areas of Guinean savannah, also known as mountain savannah, are also present (Brunel *et al.*, 1984). Zone V, the coastal plains, is characterized by a mosaic of vegetation, including fallow land, crops, scrubland, savannah, and small pockets of forest (Kokou et Sokpon, 2006). Mangroves and floodplain savannahs can be found in the far south-east of the country (Guelly *et al.*, 2020).

2. Data collection

Occurrence data of Fonio

The five ecological zones of Togo were the setting for fieldwork during which the locations and cultivation areas of fonio (in terms of longitude and latitude) were recorded using the MAPS.ME mobile application. To enhance the precision of distribution models (Fitzpatrick et Hargrove, 2009), and address the knowledge gaps, supplementary presence data for

West Africa were obtained from the GBIF platform (Global Biodiversity Information Facility, www.gbif.org) and scientific publications that referenced the existence of cultivation areas outside Togo (Kaczmarek *et al.*, 2023). A total of 4,149 presence points were considered (Figure 1): 176 came from the fieldwork; 2,279 came from Kaczmarek *et al.* (2023); and 1,694 came from the GBIF platform.

Environmental data

To model the potential fonio cultivation area, 21 environmental variables were used, including 19 bioclimatic variables,

soil type and altitude (Table I). The bioclimatic variables and altitude data were obtained from the WorldClim 2.1 database (<https://www.worldclim.org/data/worldclim21.html>). Soil data were obtained from the Harmonized World Soil Database (<http://www.data.tpdc.ac.cn/en/data/84410ba-d359-4020-bf76-2b58806f9205/>) (Atakpama *et al.*, 2022a). Two Shared Socio-economic Pathways (SSPs) radioactive forcing scenarios were used to estimate future climate projections for the year 2055. The first is the optimistic scenario (SSP126) and the second is the pessimistic scenario (SSP585). The first scenario involves a moderate increase in greenhouse gas

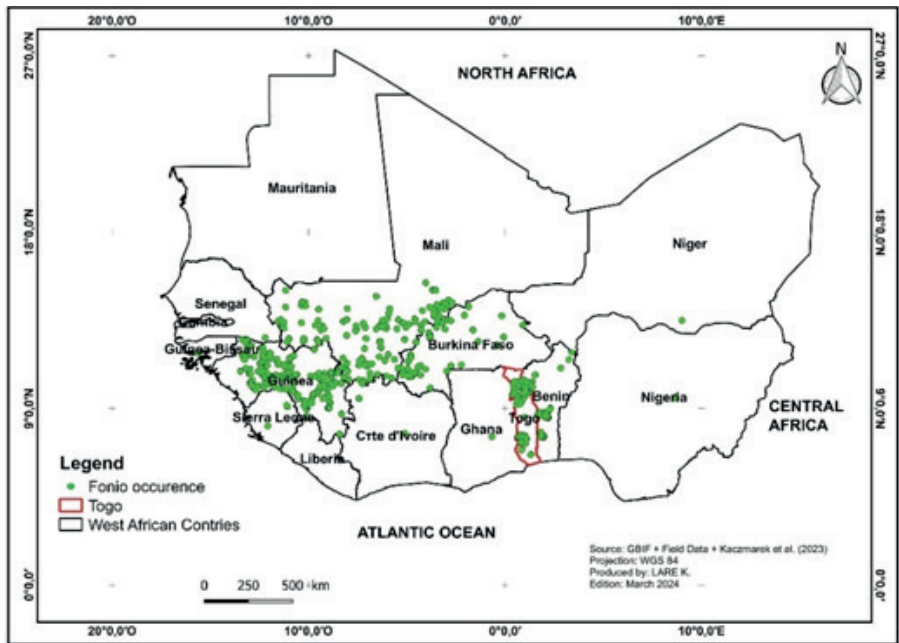


Figure 1. Occurrence of Fonio in West Africa.

Table I. Dynamics of fonio cultivation areas according to ecological zones (%)

Ecological Zones		Zone I	Zone II	Zone III	Zone IV	Zone V
SSP 126	Highly favourable	-4.2	-1.58	-2.16	-2.05	22.58
	Moderately favourable	0.19	71.13	-1.22	42.76	68.93
	Less favourable	13.34	0	7.91	-16.8	38.66
	Unfavourable	123	0	26.96	-24	-34.25
SSP 585	Highly favourable	-4.42	-0.5	-10.77	-0.17	-49.46
	Moderately favourable	8.46	22.18	4.72	9.65	11.52
	Less favourable	9.17	0	36.21	-5.44	-9.16
	Unfavourable	79.67	0	-0.64	-7.43	2.58

emissions. The second reflects a more dramatic increase in emissions (IPCC, 2014). All environmental layers have a spatial resolution of 30 seconds (1 km x 1 km). GIS software (QGIS 3.16 and ArcGIS Pro) was used to cut these layers according to the boundaries of West Africa and to format the environmental variables for modelling.

Execution and validation of the model

The methodology used is statistical or correlative modelling based on the Maximum Entropy (MaxEnt) algorithm. MaxEnt is an independent Java programme based on artificial intelligence that is used to predict species distributions (Phillips *et al.*, 2006). The programme is able to generate high-quality biogeographical information and accurately identify habitats that are suitable for a species from a bioclimatic viewpoint (Atakpama *et al.*, 2022a). It has already been successfully used to model the

habitats of several socioeconomically important species in West Africa (Salako *et al.*, 2019 ; Dimobe *et al.*, 2020 ; Avaligbé *et al.*, 2021 ; Assang *et al.*, 2023 ; Samarou *et al.*, 2023). Its standout feature is its capacity to process both categorical and continuous data (Phillips *et al.*, 2006). Absence data is not required, as these are difficult to collect (Urbina-Cardona et Loyola, 2008) and, even when available, can be uncertain in many situations (Anderson *et al.*, 2003). It also performs well in predicting species distribution in landscapes that have been little studied (Hernandez *et al.*, 2008).

To reduce spatial autocorrelations, which can be caused by insufficient data collection in certain areas, a single occurrence point was considered for each 1 km x 1 km pixel. The model was calibrated using 75% of the occurrence points. The remaining 25% were used to test it. The model was run using all pedoclimatic variables (Moukrim *et al.*, 2020 ; Atakpama *et al.*, 2022a).

The Receiver Operating Characteristics Curve index (Rocheleau *et al.*, 1998) was used to test the model's performance. This index is obtained by calculating the area under the curve (AUC). The AUC values were interpreted in line with the proposal by Araújo *et al.* (2005): AUC values of 0.5–0.7 indicate a poor model, 0.7–0.9 a good model, and >0.9 an excellent model. The contribution of each variable used in the model was assessed using the jackknife test (Moukrim *et al.*, 2019).

3. 3. Habitat mapping

The results from the West Africa-scale modelling were imported into QGIS 2.18 software, which is used for analysing geospatial data. Extraction in accordance with Togo's boundaries and categorization allowed the identification of different fonio habitats based on the logistical likelihood of occurrence (P). With reference to the mean threshold (T) value, four categories of habitat were delineated: unfavourable, less favourable, moderately favourable and highly favourable. Habitats where $P \geq T$ are considered to be highly favourable. Those where $T/2 \leq P < T$ are regarded as being moderately favourable. For habitats that are less favourable, the ratio $T/4 \leq P < T/2$. Unfavourable habitats correspond to $P < T/4$. The dynamics of future habitats were deduced by calculating the areas of each type of habitat identified (Atakpama

et al., 2022a). These differences were expressed as rates by multiplying them by 100 and dividing them by the current habitat area. Progression is indicated by a positive proportion in a habitat, while regression is indicated by a negative proportion.

4. Priority areas for fonio cultivation

Version 4.0 of the Zonation software was used to determine the priority areas for fonio cultivation (Atakpama *et al.*, 2022a). This software allows landscapes to be classified to identify priority habitats while highlighting their quality (Rabenandrasana *et al.*, 2018). The input files are TIF images of the current potential habitat, as well as the SSP 126 and SSP 585 predictions from the modelling for the future. The outcome of the zoning process is a raster file that has been divided into zones, with zones ranging from very high priority to very low priority. Areas with a value greater than 0.98 are given very high priority, while those with a value less than or equal to 0.2 are considered very low priority.

RESULTS

1. Current and future potential areas for fonio cultivation

1.1. Model validation

The average area under the ROC curve (AUC) measuring the predictive

accuracy of the *Digitaria exilis* model is 0.92. This demonstrates the robustness and excellent predictive power of fonio cultivation areas. The annual temperature range (BIO 7) variable had the greatest impact, followed by temperature seasonality (BIO 4), the monthly average of daily variations (BIO 2) and annual precipitation (BIO 12). Soil remains an important variable in model construction (Figure 2).

1.2. Current potential areas for fonio cultivation

Almost 63.69% of Togo's land is highly suitable for growing fonio. Only

9.19% of the country is considered unsuitable for fonio cultivation. Ecological zones I, II, III and IV have many habitats that are highly favourable for fonio cultivation. Zone II is predicted to be the most suitable for fonio cultivation. In contrast, ecological zone V is predicted to be very unsuitable for cultivation. In terms of economic regions, areas with high potential for fonio cultivation are located in the Kara and Central regions (Figure 3). The Plateaux and Savannah regions are moderately favourable. However, just over two thirds of the Maritime region is virtually unsuitable.

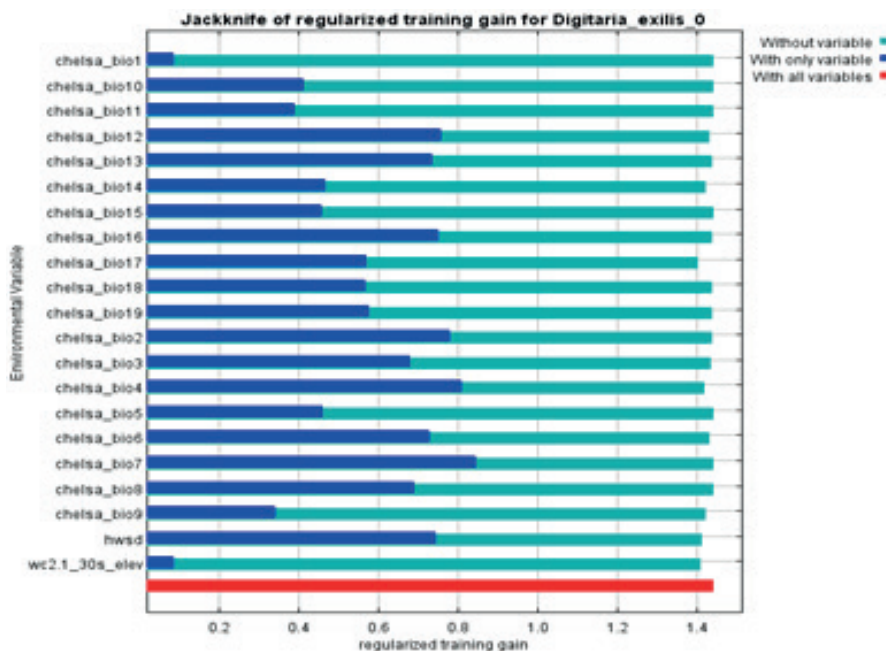


Figure 2. Contribution of variables in modelling according to the Jackknife test.

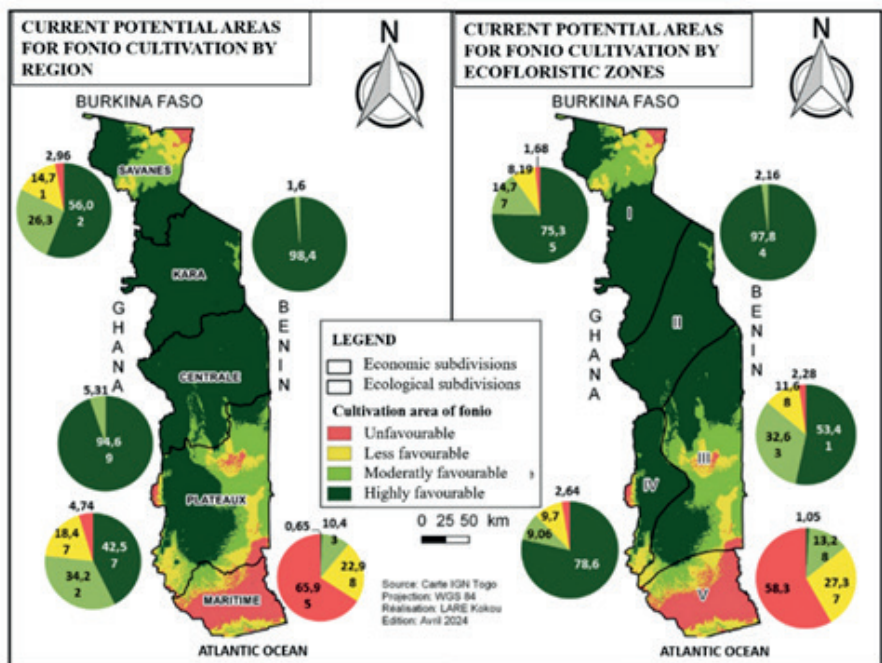


Figure 3. Current potential area for fonio cultivation in Togo.

1.3. Potential area for fonio cultivation by 2055

Both scenarios predict that ecological zone V will continue to be the least favourable for fonio cultivation (Figure 4). The SSP 126 scenario predicts a 34.25% decline in unfavourable habitats, with the others increasing in size. In contrast, the SSP 585 scenario predicts an increase in moderately favourable habitats (11.52%) and a decline in unfavourable habitats (2.58%), at the expense of less favourable and highly favourable habitats. Despite the decline (-1.58% under the SSP 126 scenario and -0.5% under the SSP 585 scenario),

ecological zone II will remain the most favourable for fonio cultivation under both scenarios. Most of ecological zones I and IV will also be favourable for fonio cultivation. However, these zones will experience a decline of around 4.2% and 2.05% (SSP 126) and 4.42% and 0.17% (SSP 585) respectively. According to both scenarios, zone V will experience the highest rate of increase in unfavourable habitats.

2. Impact of climate change on growing areas

Figure 4 shows that the impact of future changes on fonio production areas

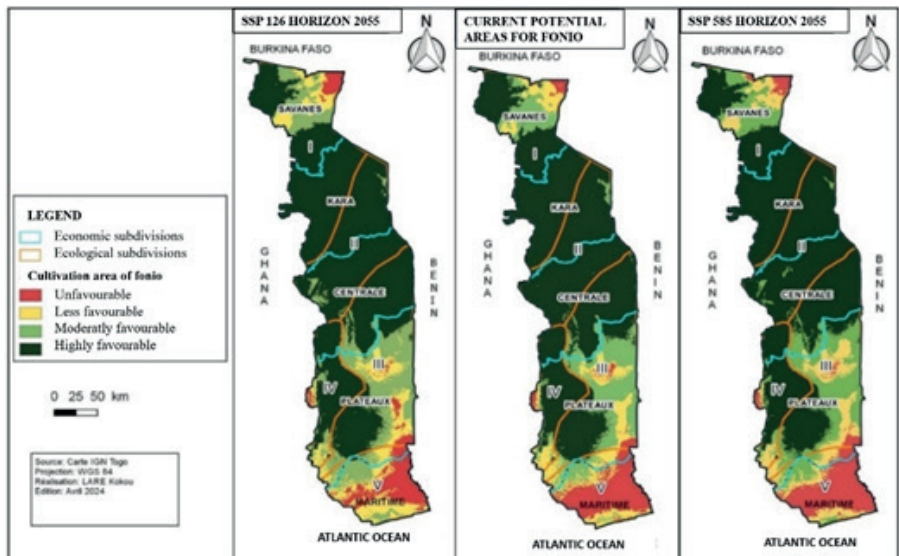


Figure 4. Current and future potential areas for fonio cultivation.

would vary according to ecological zones and economic regions. Despite the decline in the Central Region, the Kara and Central regions will remain the most favourable areas for fonio development under both scenarios. In the Kara region, the rate of increase in highly favourable habitats is 0.79% under the SSP 126 scenario and 1.12% under the SSP 585 scenario. In contrast, the rate of decline in these habitats is 2.90% and 4.37%, respectively, in the Centrale region. According to the SSP 126 scenario, the Maritime region will experience the highest increase, at 58.31%, while the Kara region will experience the highest increase (1.12%) according to the SSP 585 scenario. Conversely, the Savannah region will

experience the greatest decline (-9.93% under SSP 126 and -10.56% under SSP 585) by 2055. The Maritime region is the least favourable area, with 41.83% of habitats deemed unfavourable under the SSP 126 scenario and 66.63% under the SSP 585 scenario.

Comparing the current model with future scenarios reveals a slight decline in highly favourable habitats and a slight increase in moderately favourable ones, regardless of the scenario (Figure 4; Table I). SSP 126 predicts a 2.57% decline in highly favourable habitats and a 21.39% decline in unfavourable habitats, while moderately and less favourable habitats are predicted to increase (Figure 5). SSP 585 predicts a decline in highly favourable habitats

in favour of the others. This scenario forecasts increases in moderately favourable, less favourable and unfavourably suitable habitats of 6.92%, 10.73% and 5.78% respectively (Figure 5). The rates of increase in moderately and poorly favourable habitats under this scenario are significantly lower than those predicted by SSP 126. Regarding unfavourable habitats, SSP 126 predicts a decline of 21.39%, whereas SSP 585 predicts an increase of 5.78%.

3. Priority areas for fonio cultivation in Togo

The areas that are the highest priority for sustainable fonio cultivation are located in the Kara region and the north-

west of the Plateaux region (Figure 6). A few additional high-priority areas are found in the north-east, centre and southwest of the Central region, and in the south-east of the Savannah region. Non-priority areas cover almost the entire Maritime region and the southwest of the Plateaux region, as well as the northern part of the Savannah region.

DISCUSSION

1. Current and future potential habitats

The variables that contributed most to the construction of distribution models for areas favourable to *Digitaria exilis* were the annual temperature range,

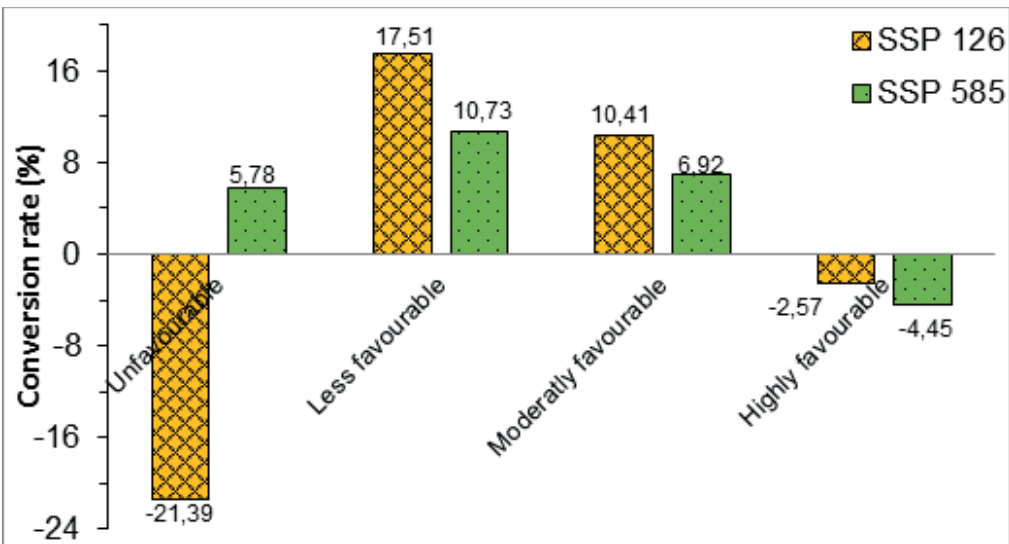


Figure 5. Dynamics of potential fonio cultivation areas.

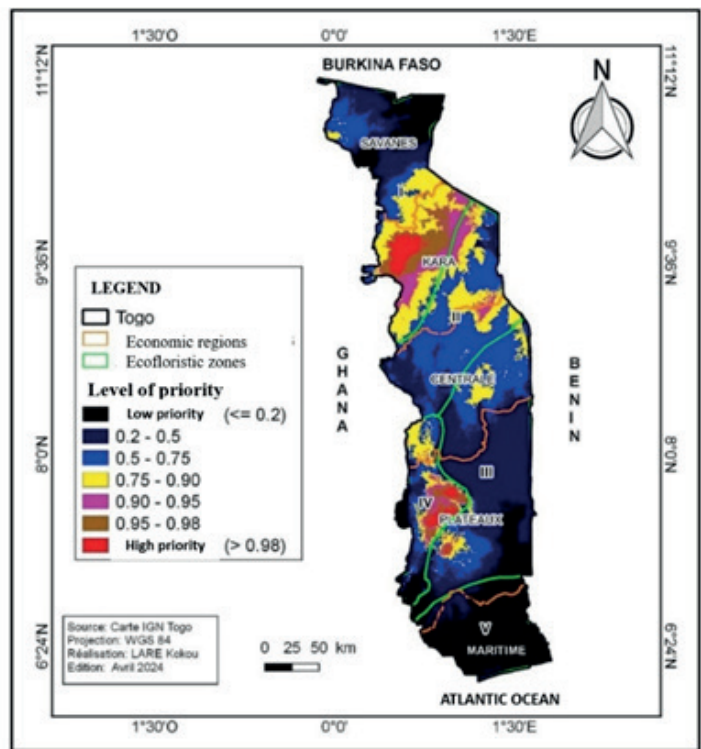


Figure 6. Priority areas for the fonio cultivation in Togo.

temperature seasonality, monthly average of daily variations and annual precipitation. These results are comparable to those of Gbesso *et al.* (2013) and Fandohan *et al.* (2013) regarding the distribution of *Chrysophyllum cainito* and *Tamarindus indica* in Benin. This demonstrates that climatic factors primarily influence the distribution of plant species. The annual temperature range and the monthly average of daily temperature variations influence soil water availability and evapotranspiration. This directly

impacts the physiological development of the plant. Temperature variation has little effect on fonio cultivation. In fact, this crop thrives in areas where the average temperature is around 20 °C (Froment et Renard, 2001). According to Froment et Renard (2001), fonio requires rainfall of between 750 and 1,250 mm, with the majority of crops being grown within the 900–1,000 mm range. This would explain why there are so many habitats favourable to fonio throughout the country.

2. Impact of climate change on the distribution of fonio cultivation areas

Some favourable habitats are currently located in areas where fonio is not cultivated. This corroborates the finding that the fundamental niche of a species is, in all instances, more expansive than its actual habitat (Gouwakinnou, 2013; Atakpama *et al.*, 2016 ; Kombate *et al.*, 2024). Consequently, the full potential cultivation area for fonio remains untapped. Habitats favourable to fonio cultivation are mainly found in the northern plains and mountains, the Sudano-Guinean savannahs, and the southern part of the Togolese Mountains (ecological zones I, II, and III) (Ern, 1979). These areas meet the optimal ecological requirements for fonio cultivation. Areas at risk for cultivation are mainly located in the south of the country, specifically in the Maritime region. The low altitudes that characterize these areas are not favourable for the species. Indeed, fonio is a crop better suited to high-altitude conditions (Vodouhe *et al.*, 2003).

No matter what the scenario, there will be a slight decline in the areas that are currently suitable for growing fonio, with these areas being replaced by moderately and poorly suitable habitats. These findings echo those of Dimobe *et al.* (2020) regarding the Shea butter tree in Burkina Faso, and Gbesso *et al.*

(2013) concerning the African star apple (*Chrysophyllum albidum*) in Benin. One of the predicted effects of climate change is an increase in temperature and more erratic rainfall (Pachauri et Reisinger, 2008). The agriculture and forestry sectors would be severely affected, particularly in Africa where agriculture depends heavily on rainfall (Pachauri et Reisinger, 2008 ; IPCC, 2014). This could directly impact cereal productivity, including the cultivation of fonio (Chebil *et al.*, 2011 ; Konte et Soumaoro, 2022).

3. Priority areas for fonio cultivation

In addition to being very favourable for fonio cultivation, the Kara region and north-west Plateaux are priority areas for fonio cultivation in Togo. Fonio adapts best to the Sudano-Guinean zones, where the average annual temperature ranges between 25 and 29°C (Oyen and Lemmens, 2002). These conditions correspond well to fonio's requirements. The cultivation of fonio in these areas will be less affected by future climate change.

Limit of the study

The present study only takes climate parameters into account. It does not consider biotic or parasitic parameters, which are important for cultivation.

Climate parameters are the most commonly used for modelling (Assang *et al.*, 2023 ; Avaligbé *et al.*, 2021 ; Dimobe *et al.*, 2020). These parameters are the most accessible and straightforward to use for modelling purposes. Another limit is the failure to consider varietal and genetic variation. This parameter has been shown in previous studies to be essential for strengthening models (Atakpama *et al.*, 2023). Unfortunately, the species was considered on a global scale during this study

CONCLUSION

The environmental variables that most influence the spatial distribution of potential fonio growing areas are the annual temperature range, seasonal temperature variations, monthly average daily temperature variations and annual precipitation. Under current climatic conditions, around 63.69% of the country is highly suitable for fonio cultivation. These areas are primarily found in the Kara and Central regions, but are expected to decline slightly by 2055. Therefore, fonio could be a resilient crop in the face of climate change. The Kara and Plateaux regions are home to the priority areas for fonio cultivation by 2055. These results must be considered in development policies to ensure the long-term preservation of

fonio in Togo. Securing the nutrition of the local population and generating revenue is dependent on selection and varietal development.

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