Using climate indices to forecast food security? – classification and change of (un)favourable areas for the cultivation of maize (*Zea mays* L.) in West Africa

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1. Introduction

Climate change poses a significant threat on agriculture and therefore overall food security. This is particularly true for West Africa – a region that is highly vulnerable to climate change and variability due to a combination of substantial reliance on rainfed agriculture, limited adaptative capacity and fast-growing population.[1] In order to address the major challenge of food security, it is crucial to identify future potential changes in crop cultivation areas at the regional level. Such an analysis was conducted for maize (*Zea mays* L.) which is one of the most important staple foods in West Africa accounting for about 20 % of the overall calorie intake.[2] While numerous studies focus on this topic using different models, scenarios and indices, we want to use basic climate variables – temperature (mean, max) and precipitation – to not only model potential shifts in (un)favourable cultivation areas, but also see whether these applications are valid to forecast crop climatic conditions ultimately relating to food security.

2. Study Area

The geographical region of West Africa comprises fifteen countries, a total population of roughly 420 million and is divided into three FAO Agro-Ecological Zones: Guinea (4 – 8 °N), Savanna (8 – 12 °N) and Sahel (12 – 20 °N).[3, 4] Climatically, there is an increase of precipitation and decrease of temperatures from North to the South. The seasonal cycle is driven by the West African Monsoon which is the major system influencing onset, variability and pattern of precipitation and is predicted to shift in the face of changing climate.[4] This is a substantial risk for the agricultural sector: two thirds of the West African population are occupied in subsistence farming of which 95 % are rainfed and food provision is already insecure with a large share of the population facing malnutrition.[1] Thus, climate change will negatively affect crop growth, including the staple crop maize – a thermophilic plant highly susceptible to drought.[5] Especially the (uneven) distribution of precipitation during rainy season may cause severe yield losses in the area with predictions ranging from 7 to 22 % by 2050 up to 37 % losses by the end of the century. [5, 6, 7]

3. Materials and Methods

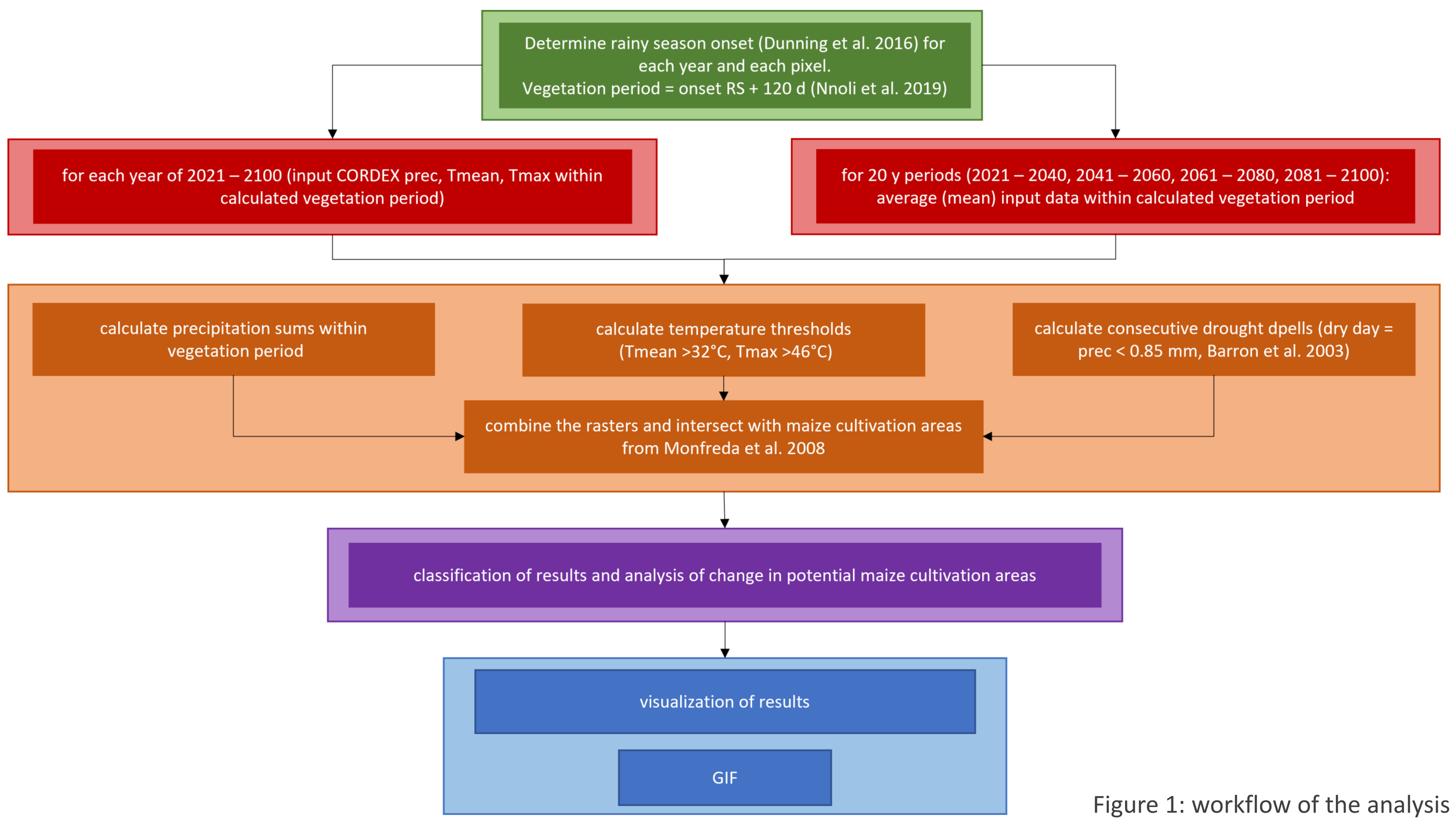


Figure 1: workflow of the analysis

In this analysis, dynamically downscaled CORDEX data from 2021 to 2100 were processed with R Studio. The CCCMAs' driving model CanESM2 and the representative concentration pathway to 4,5 Wm^{-2} were chosen. The CORDEX Africa data has a spatial resolution of 22° x 22° and daily temporal resolution. The climate variables analyzed are precipitation, maximum near surface air temperature and mean near surface air temperature because these are both important in determining climate change impacts while also having a significant effect on crop yield.[1]

To ensure that only actual cultivation areas are processed, the data was masked with the resampled maize cultivation areas of Monfreda et al. (2008). After preprocessing the data, the rainy season onset for each pixel and each year was calculated using the methodology of Dunning et al. (2016). The vegetation period is set to 120 d starting with rainy season onset.[9] As visualized in the workflow-chart in figure 1, the analysis was conducted for three crucial crop growth indicators for a) each year and b) 20-year averaged (mean) periods: precipitation sums, temperature thresholds and maximum drought spell length during the vegetation period. Extensive literature review of maize growing conditions allowed synthesis of a classification scheme which was used to systemize the results and show the change of (un)favourable cultivation areas over time.

4. Results

Table 1: classification of crop growth conditions based on precipitation sums, temperature thresholds (mean, max temp) and drought spell lengths

	DS 1	DS 2	DS 0
P1 T1	optimum growth	risk slight yield reduction	risk yield loss
P2 T1/ P1 T2	risk slight yield reduction	risk severe yield reduction	risk yield loss
P2 T2	risk severe yield reduction	risk severe yield reduction	risk yield loss
P0 T1/ P0 T2/ P0 T0/ P1 T0/ P2 T0	risk yield loss	risk yield loss	risk yield loss

classification: optimum growth = 1, risk yield reduction = 2, risk crop failure = 0

Precipitation sums
P1: 600 – 1200 mm [1, 10, 11, 12]
P2: 400 – 600 mm & 1200 – 1800 mm [1]
P0: < 400 mm & > 1800 mm [1]

Temperature thresholds
T1: T mean 15 – 32 °C [10, 11]
T2: T mean über 32 °C [11]
T0: T max über 46 °C [1, 5, 7]

Drought Spells (Dry day = prec < 0.85) [8]
DS1: DS <5 d [9, 13]
DS2: DS 5-13 d [9, 14]
DS0: DS >13 d [14]

4.1 Classification and impact of single variables

The classification scheme derived from literature is shown in table 1. The results of applying the single indicators' classification onto the study area are illustrated exemplary for the period 2041 – 2060 and plotted by total area for all periods in figure 2 (see attachment for complete dataset). The different indices have very different impacts on maize cultivation. Especially heat days seem to limit crop growth: in about 36 % of the area maximum temperatures exceed 46 °C and thus are classified with risk of yield loss in the first period. Until the end of the century the optimum temperature area decreases from 59 % to 49 % with an increase in both risk of yield reduction (6 % to 10 %) and risk of yield loss (36 % to 40 %). Precipitation sums are within the optimal range of 600 – 1200 mm in about 60 % of the area; approximately one third show risk of yield reduction. Drought spells seem to have the smallest negative impact on maize cultivation with about 80 % of the area being classified as optimal and almost no drought spell lengths exceeding 13 d risking crop failure. Until the end of the century, there are only minor shifts in total area within each class for both precipitation and drought spells. Regarding spatial distribution, there is a clear zoning of temperature thresholds which are exceeded in the Sahel, a transition with all three categories in Savannah and optimal growing conditions in Guinea. Both precipitation and drought spell impacts show a more scattered spatial distribution locally posing threats in maize yields: for instance, the Sahel is partially affected by suboptimal precipitation sums, so is the coastal zone of Ghana and the Nigerian-Cameroonian border.

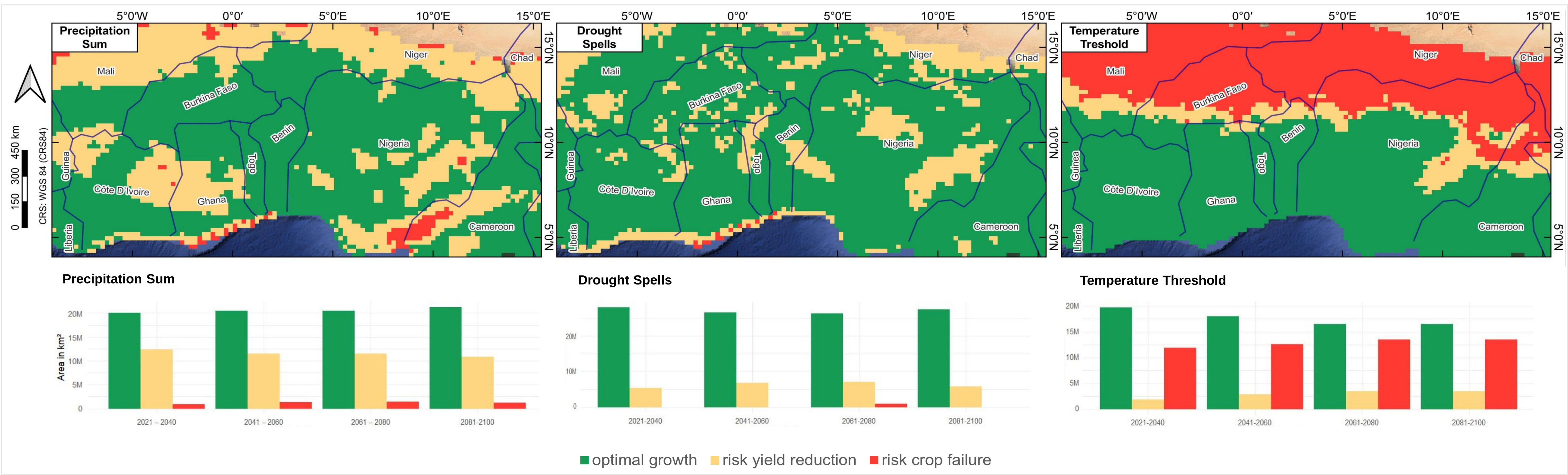
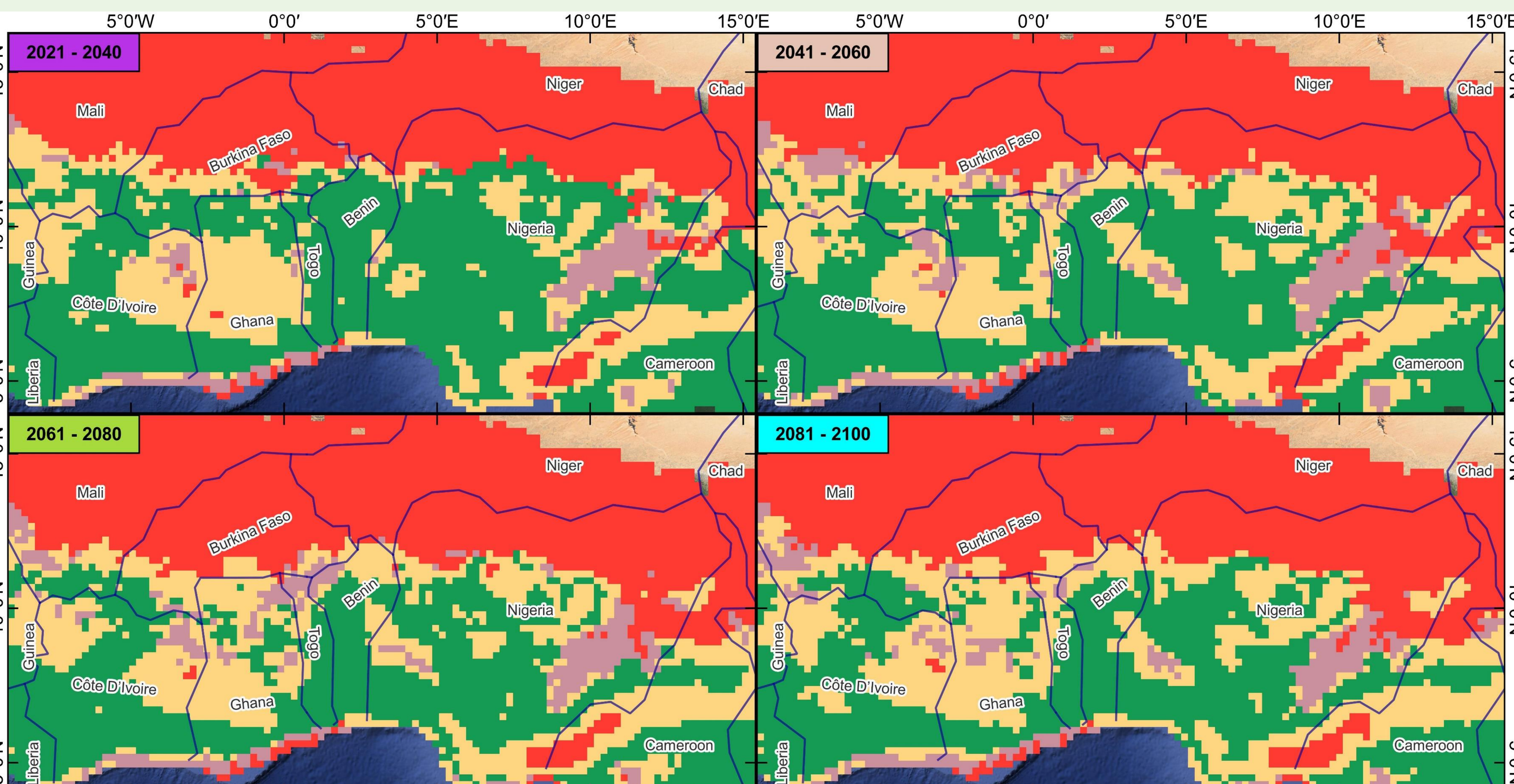


Figure 2: Above - impact of itemized crop growth indicator classification for the period 2041 – 2060. Below – total area distribution of each indicator class for all periods*



	2021 - 2040		2041 - 2060		2061 - 2080		2081 - 2100	
Classification	Area[km²]	%	Area[km²]	%	Area[km²]	%	Area[km²]	%
optimal growth	12,557,921	37.55	10,806,887	32.32	9,781,029	29.25	9,651,323	28.86
risk of slight yield reduction	7,245,862	21.67	7,599,606	22.73	7,605,502	22.74	8,088,952	24.19
risk of severe yield reduction	1,338,332	4	1,963,281	5.87	2,063,508	6.17	1,751,034	5.24
risk of crop failure	12,298,509	36.78	13,070,850	39.09	13,990,585	41.84	13,949,315	41.71

Figure 3: final classification results of the three crop growth indicators (precipitation sum, drought spells, temperature threshold) and their impact on maize cultivation in four averaged periods from 2021 – 2100*

4.2 combined classification and change over time

Figure 3 illustrates the combined classification of all three variables for the four periods ranging from 2021 – 2100. In the first period, there is an equal number of areas with optimal growth conditions and crop failure – both about 37 %. One fourth of the area face risk of yield reduction. There is a clear zonal distribution with the Sahel zone being most vulnerable to crop failure. Guinea and Savanna zone are generally well suited for maize cultivation with scattered zones of yield reductions and few areas with risk of crop failure. Over time, the optimal growth condition area declines by about 10 % to 29 % in 2081 - 2100; leading to an increase in both risk of yield reduction and risk of crop failure by about 5 % until the end of the century. In 2081 – 2100, 42 % of the area are at risk of no longer being suited for maize cultivation making it the prevailing class. Especially the Sahel zone crop failure area seems to expand southward, whereas the remaining spatial distribution shows only insignificant changes over time. The classification results with annual resolution are presented in this GIF in the attachment:

5. Discussion and Conclusion

Our analysis shows that by the end of the century, unfavourable areas for maize cultivation in West Africa will increase by roughly 10 % - these results align with prior modellings of the region.[5,7] Depending on the limiting crop growth variable, different adaptation methods may be required: too little precipitation or drought spells can be overcome with rainwater harvesting techniques, mulching or supplementary irrigation, whereas increasing heat days can be addressed e.g., by switching to more heat-resilient maize species.[1, 9, 15] Regarding our classification, especially the temperature thresholds limit crop growth, whereas drought spells play a less significant role – in contrary to previous studies on the issue.[8, 9, 12, 14] This raises the question how well suited the climatic indices and derived crop growth parameters are for classifying maize cultivation. Firstly, there are potential errors due to the classification with its hard-set boundaries itself. The margins can only be general benchmarks and do not consider changing vulnerability throughout different crop growing stages, specific local conditions, potential stress priming effects, etc. Secondly, using solely climatic indices for modeling an agronomic variable is inherently flawed since soil parameters are not accounted for. Further indices like soil moisture, water storage capacity and evapotranspiration rates would enhance the validity of the results. Other potential errors to keep in mind when interpreting the results are the large possible range of future climate developments which are not addressed when using only one representative concentration pathway as well as the CORDEX downscaling method as an additional source of uncertainties.[2] When considering these constraints, the approach of modelling food security by using downscaled climate indices can be a good addition to other analyses: it allows spatial distinction of future potential developments and itemizing of single parameter impacts, making targeted adaptation possible.

*Derived from daily resolved CORDEX data (maximum air temperature, mean air temperature, precipitation). For each 20-year period, input data were averaged (mean) for the 120 d maize vegetation period within annual rainy season

References:
Follow QR Code in section 4.2 to attachment for reference list

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