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CACCI FIELD NOTES

Spatial Distribution of Climate Risk and Vulnerability in Senegal

Aïssatou Ndoye, Khadim Dia, and Mansour Dia

About the CACCI Field Notes

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Published on the AKADEMIYA2063 website (open access), CACCI Field Notes provide broad and timely access to significant insights and evidence from our ongoing research activities in the areas of climate adaptation and mitigation. The data made available through this publication series will provide evidence-based insights to practitioners and policymakers driving climate action in countries where the CACCI project is being implemented.

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AKADEMIYA2063 is committed to supporting African countries in their efforts against climate change through provision of data and analytics using the latest available technologies. In this Field Note, AKADEMIYA2063 scientists use remote sensing methods to describe Senegal's context in terms of climate-related variables such as surface water, rainfall, land use and land cover, drought intensity, and soil properties at the pixel level.

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Authors:

Aissatou Ndoye is an Associate Scientist at AKADEMIYA2063: andoye@akademiya2063.org.
Khadim Dia is a Senior Associate Scientist at AKADEMIYA2063: kdia@akademiya2063.org.
Mansour Dia is an Associate Scientist at AKADEMIYA2063: mdia@akademiya2063.org.

1. Introduction

Climate change is a complex problem with far-reaching economic, environmental and social impacts in many countries worldwide. Senegal in West Africa faces a particularly high risk of being affected by climate change due to its geographic, economic, and social conditions. With its long coastline and reliance on rain-fed agriculture, the country is vulnerable to the impacts of higher temperatures, changing rainfall patterns, and rising sea levels. The Government of Senegal has initiated several measures to address the complex challenges raised by climate change, including the development of a national plan for climate change adaptation. However, the country still has a long way to go to ensure that it is adequately equipped to handle the impacts of climate change and strengthen the resilience of its communities.

Senegal's economy is heavily dependent on agriculture, with about 70 percent of the population engaged in agriculture and related activities (FAOSTAT 2013). However, climate variability has been a significant challenge for Senegal's agricultural sector. The country continues to experience extreme weather events such as droughts, floods, and heat waves, which can severely impact crop yields as well as the livelihoods and well-being of millions of people. Given this context, it is essential to understand the main climate variables affecting Senegalese farmlands, including precipitation, temperature, water, and soil properties. Understanding these variables and their impacts is critical to developing effective climate change adaptation and resilience strategies for agriculture as their variability directly impacts crop productivity and farmers' livelihoods. Senegal is looking to develop more resilient agricultural practices and technologies to help mitigate the effects of climate change on crop yields.

Variations in climatic variables, weather patterns, and climatic conditions can differ significantly depending on location. As a result, different ecosystems and human societies will experience disparate climate change impacts, and certain regions may be more vulnerable than others. It is crucial to comprehensively monitor climatic variables to determine the current state of the Earth's climate and create approaches for coping with climate change. Understanding the climatic variables that influence a particular region is essential for predicting weather patterns, planning agricultural activities, and managing natural resources in the context of climate change.

This report examines several climatic variables such as surface water, rainfall, land use and land cover, drought intensity, and soil properties at the pixel level. Rainfall patterns vary widely within Senegal, with the country's north getting less rainfall than the south. The rainy season usually lasts from June to October, with the heaviest rain falling between July and September. Farmland is a critical component of Senegal's economy as agriculture accounts for about 15 percent of the country's GDP. The most important cultivated crops are millet, sorghum, rice, and groundnuts. Soil carbon is essential for soil health and fertility and is influenced by land use, vegetation cover, and soil management practices. The soil carbon content in Senegal's farmlands varies by location and soil type.

2. Surface Water Index

In this section, we used the Global Surface Water datasets from the European Union's Joint Research Center. The dataset is composed of several variables which show different aspects of the spatial and temporal distribution of Earth's surface water over the last 38 years. In this section, we focus on two variables: Change and Transitions. We extracted Senegal's data for these two variables, as well as data on rainfall anomalies. These are described below.

2.1. Changes in Water Occurrence

The variable, occurrence change intensity, provides information on water occurrence in distinct locations. It shows whether water occurrence increased, decreased, or remained the same between 1984 and 2021 as well as the changes in water occurrence intensity between two periods, viz., 16 March 1984 to 31 December 1999, and 1 January 2000 to 31 December 2021. The data is derived from homologous pairs of months (i.e., the same months contain valid observations in both periods) and they provide a consistent estimation of the changes in water occurrence.

Table 1: Description of water occurrence change bands

Name	Description
Change_abs	The absolute difference in the mean occurrence value between the two periods for homologous months.
Change_norm	The normalized difference in the mean occurrence value between the two periods for homologous months (epoch1 - epoch2/epoch1 + epoch2).

Table 2: Classification of Tiff change_norm band based on value: The values from 0 to 200 are discrete and correspond to -100 percent loss to 100 percent increase respectively.

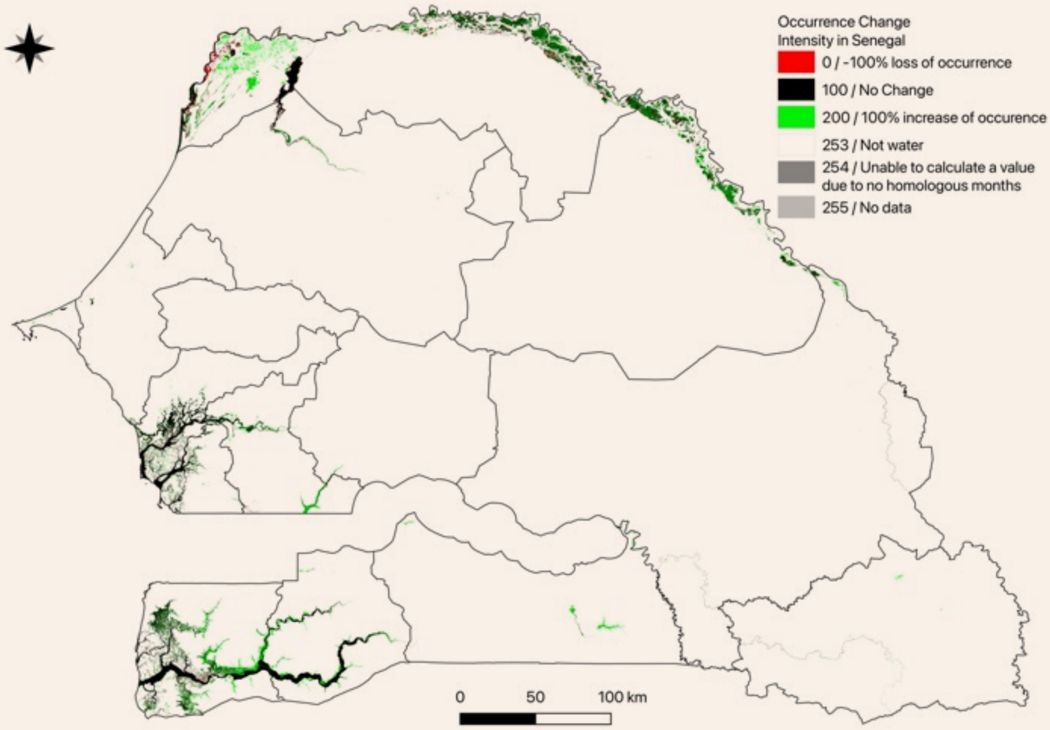
Tiff Value	Legend	Description
0	Red	-100% loss of occurrence
100	Black	No change
200	Green	100% increase in the occurrence
253	White	Not water
254	Dark Gray	Unable to calculate a value due to no homologous months
255	Light Gray	No data

Table 3: Occurrence of change values and their corresponding classes

Class of value ranges	Occurrence change (%)
-100 to -75	39.43918
-75 to -50	0.027537
-50 to -25	0.045371
-25 to -10	0.04593
-10 to 0	0.499495
1 to 10	0.113302
10 to 25	0.169317
25 to 50	0.273147
50 to 75	0.182877
75 to 100	0.299522
Not water	58.90331
Unable to calculate	0.001015

Table 3 shows statistics on the change in water surface occurrence in Senegal during the period between the observation years. Significant losses in occurrence ranging from -100 to -75 percent, representing 39.43 percent of the surface land in Senegal, are observed. These are followed by losses ranging from -10 to no change (0.49 percent). Significant increases in occurrence over 75 percent, representing 0.29 percent of the surface, followed by a gain in water occurrence ranging from 25 to 50 percent, are also noted.

Figure 1: Water occurrence change intensity in Senegal.



Data source: Surface Water Body dataset; Data processing and mapping: Authors.

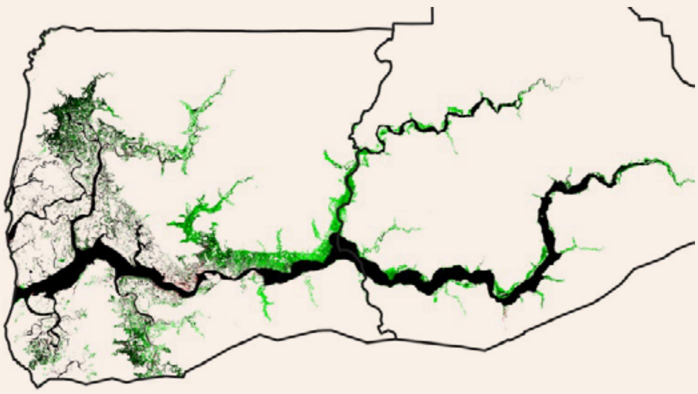


Figure 2: Occurrence change intensity in Senegal/ Casamance River. Data source: Surface Water Body dataset; Data processing and mapping: Authors.

Figure 3: Occurrence change intensity in Senegal/ Pink Lake. Data source: Surface Water Body data-set; Data processing and mapping: Authors.

Figure 1 illustrates the changes in surface water occurrence in Senegal. More detailed examples of changes in water occurrence are shown in Figure 2 and Figure 3, which represent the Casamance River in the south and the Pink Lake in the western part of the country. Increases in water occurrence are shown in green and decreases in red, while the color intensity represents the degree of change (in percentage). For instance, the bright red areas represent more significant water losses than the light red areas. As Figure 2 illustrates, significant increases in surface water occurrence are noted in the northern part of the Casamance River and in scattered areas around the river.

In contrast, significant losses in surface water occurrence can be observed at distinct locations around Pink Lake, especially in the eastern part of the lake. An increase can also be noted in the upper northern part of the lake. However, there were no significant changes between the observation years in most of the Casamance River and the Pink Lake areas. Further, the dark areas experienced no meaningful changes in water occurrence from 1984 to 2021.

2.2. Transitions

Data on transitions provides information on the changes in surface water seasonality between the first and last years (1984 and 2021). This data also captures the changes between the three classes: not water, seasonal water, and permanent water. These last two classes (seasonal water and permanent water) are divided into sub-classes. This enables the representation of changes observed in the first and last years, but not those in the intermediate years. We mapped the following transitions:

- Unchanging, **permanent water** surfaces;
- **New permanent** water surfaces (conversion of land into permanent water);
- **Lost permanent** water surfaces (conversion of permanent water into land);
- Unchanging **seasonal water** surfaces;
- **New seasonal water** surfaces (conversion of land into seasonal water);
- **Lost seasonal water** surfaces (conversion of seasonal water into land);
- Conversion of **permanent water into seasonal water**;
- Conversion of **seasonal water into permanent water**;
- **Ephemeral permanent** water (land replaced by permanent water that subsequently disappears);
- **Ephemeral seasonal** water (land replaced by seasonal water that subsequently disappears);

An unchanging water surface means that the seasonality at that particular point was the same in the first and last year it was observed, and not necessarily that it was stable throughout the years.

There are instances where water is not present at the beginning or the end of the observation record but is present in some of the intervening years. By tracking the inter-annual patterns of such **"ephemeral"** events and their intra-annual characteristics, each pixel can be classified as either ephemeral permanent water (land replaced by permanent water that subsequently disappears) or ephemeral seasonal water (land replaced by seasonal water that subsequently disappears), depending on the duration of the observed seasonality during the period of water presence.

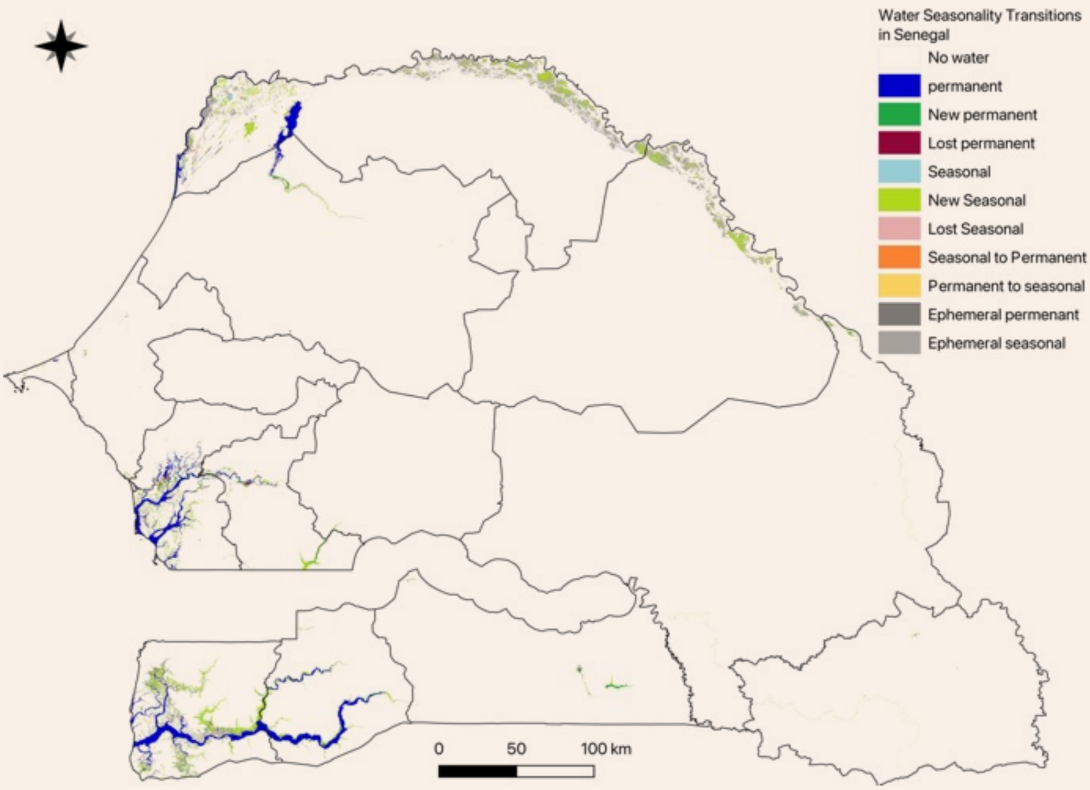
2.2.1 Statistics on Transitions

Table 4: Transition statistics on surface water seasonality by classes.

Class_Name	Covered area (%)
Not Water	98.20651825
Permanent	0.465192077
New Permanent	0.043188081
Lost Permanent	0.002737925
Seasonal	0.134581626
New Seasonal	0.489082705
Lost Seasonal	0.049323121
Seasonal to Permanent	0.048873161
Permanent to Seasonal	0.016998911
Ephemeral Permanent	0.002764136
Ephemeral Seasonal	0.540740006

Data source: Surface Water Body dataset; Data processing and computation: Authors.

Figure 4: Transitions in water seasonality in Senegal.



Data source: Surface Water Body dataset; Data processing and mapping: Authors.

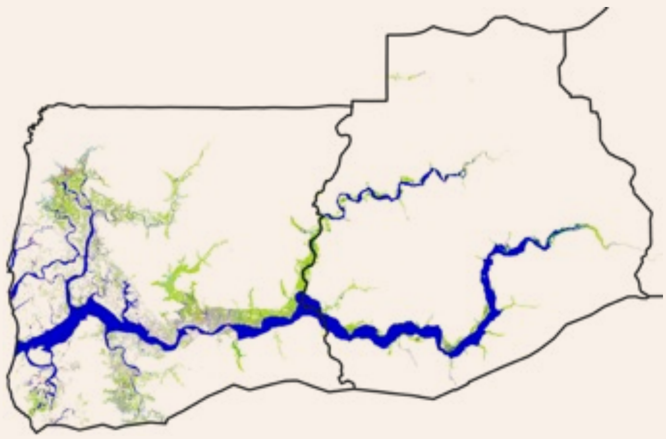


Figure 5: Transitions in water seasonality in Senegal/ Casamance River. **Data source:** Surface Water Body dataset; Data processing and mapping: Authors.

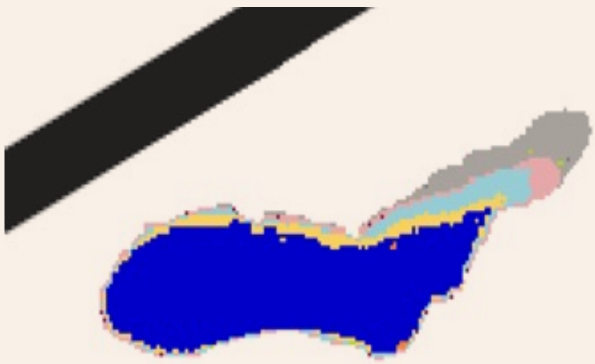
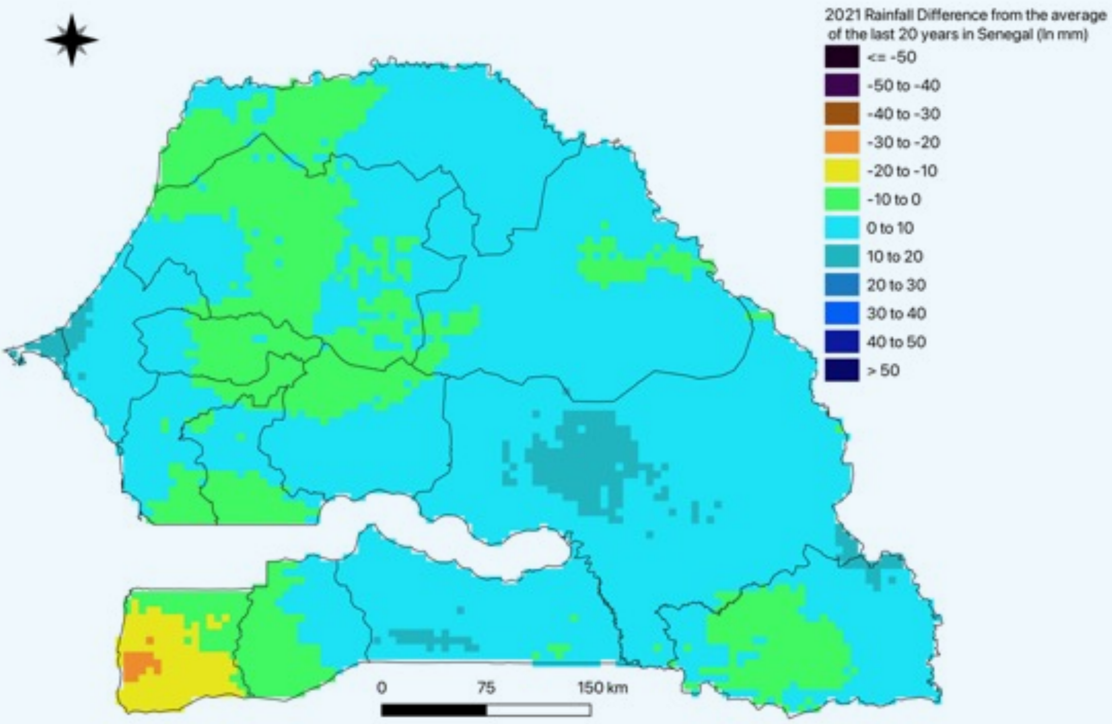


Figure 6: Transitions in water seasonality in Senegal/ Pink Lake. **Data source:** Surface Water Body dataset; Data processing and mapping: Authors.

Figures 5 and 6 show that areas in the Casamance River and Pink Lake are identified as permanent water surfaces as no change in seasonality was observed between the first and last years of observation (1984 and 2021 respectively). In contrast, the northern part of the Casamance River has new seasonal surface water, meaning the area now has seasonal surface water. This may explain the increases in water occurrence observed at these locations and the unchanged water occurrence along the river. For Pink Lake, those areas around the lake where a decrease in water occurrence was observed have changed from permanent to seasonal surface water. While seasonal surface water can also be observed, a loss in seasonality is noted at these exact locations. Notably, areas in the northern part of the lake are identified as ephemeral seasonal water bodies, representing land that is replaced by seasonal water which subsequently disappears. This may also explain why these areas are identified as increasing in water occurrence in 2021.

3. Rainfall

Figure 7: Rainfall anomalies in Senegal



Data source: CHIRPS dataset; Data processing and mapping: Authors.

A precipitation anomaly is a deviation from the average or expected precipitation pattern for a given area over a period of time. Anomalies are characterized by above-average (excess) or below-average (deficiency) precipitation in comparison to the long-term average. The rainfall anomaly between 2021 and the average of the last twenty years is computed and shown in Figure 7 using the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) datasets.

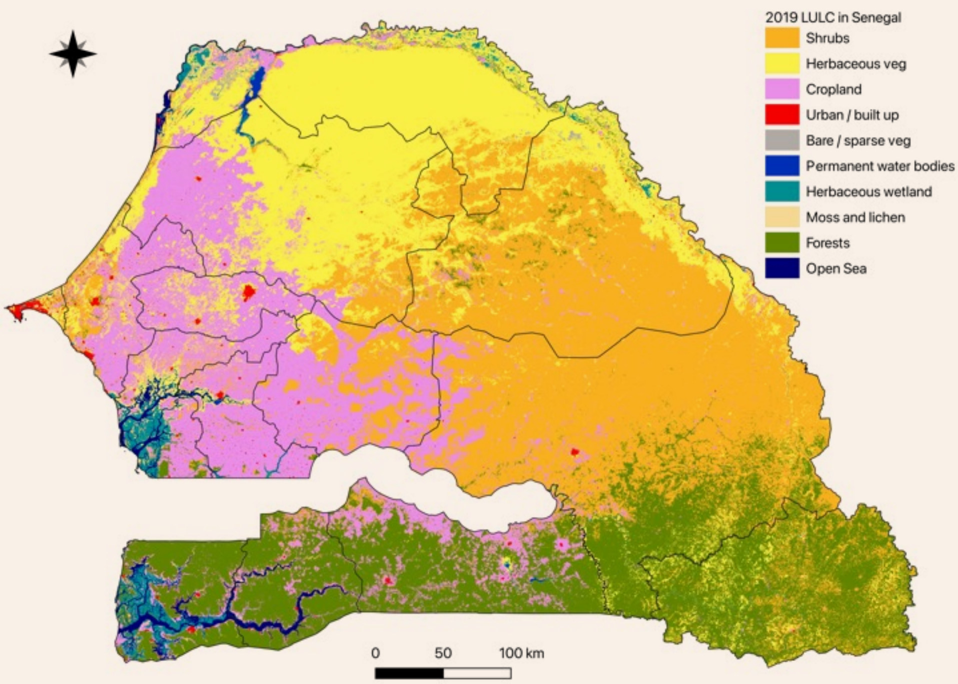
Rainfall increases below 20 mm in 2021 in comparison to the average over the last 20 years can be observed in most Senegal regions, such as Tambacounda, Matam, Kolda, Saint-Louis, and Dakar. However, significant rainfall decreases ranging from -10 to 0 mm can be observed in areas such as Saint-Louis, Louga, and Kédougou and the southern part such as Sedhiou. On the other hand, more significant decreases in rainfall can be noticed in the south, such as in Ziguinchor.

4. Land Cover in Senegal

Land cover plays a significant role in the Earth's climate systems. The term refers to spatial information on diverse types of features covering the Earth's surface, such as forests, grasslands, croplands, and water surfaces. The Land Use Land Cover (LULC) datasets publish an Annual Dynamics of Global Land Cover at a spatial resolution of 100 meters with annual updates from 2015 to 2019 that cover the entire planet. In this section, we processed data on Senegal sourced from the Copernicus Global Land Cover platform to generate Senegal's land use map. The map contains spatial information on the arrangements, activities, and inputs people use and undertake to produce, change, or maintain a specific land cover type. The land uses are classified into ten classes representing distinct types of features on the Earth's surface, e.g., forests, grasslands, croplands, lakes, and wetlands.

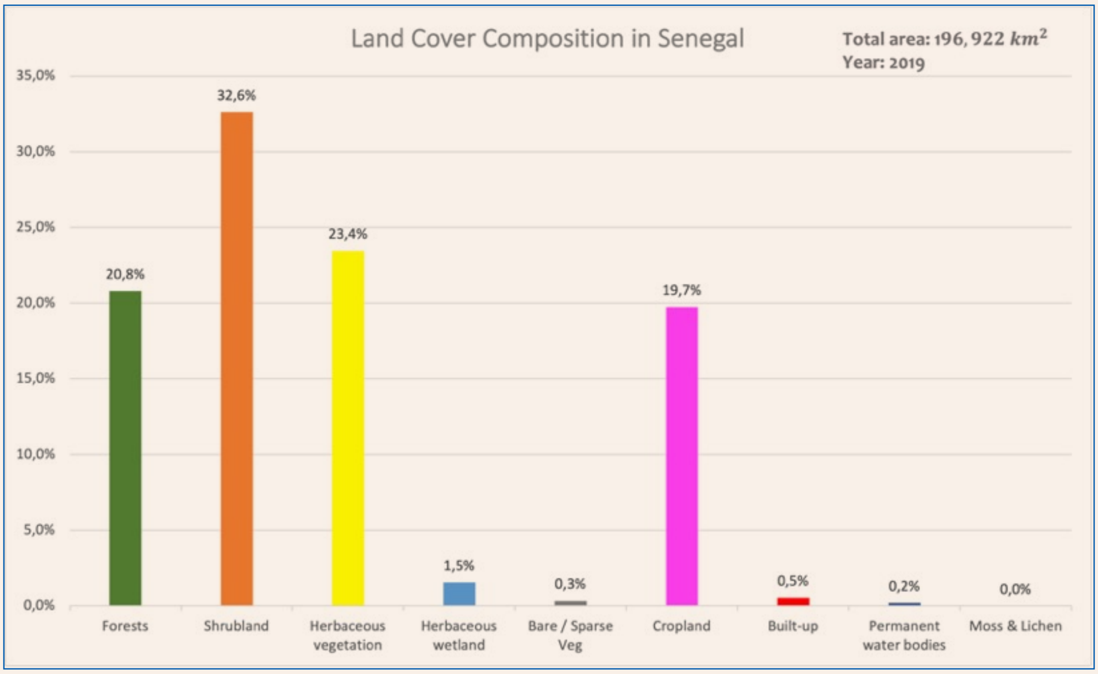
Figures 8 and 9 show that Senegal's land surface is dominated by shrublands, representing 32.6 percent of the country's total land area. This is followed by herbaceous vegetation which covers 23.4 percent of the total area, forests (20.8 percent) and croplands (19.7 percent). Other types of land uses are herbaceous wetlands (1.5 percent), urban/built-up areas (0.5 percent), bare/sparse vegetation (0.3 percent), and permanent water bodies (0.2 percent).

Figure 8: Land use and land cover in Senegal, 2019



Source: Data processing and map by authors.

Figure 9: Land cover distribution in Senegal



Source: Data processing by authors.

Notably, shrublands which represent the most significant land cover class are concentrated in the eastern areas of the country, such as Matam and Tambacounda. On the other hand, the western regions are dominated by cropland, representing 19.7 percent of the total land surface. In the northern regions, the most prevalent type of land cover is herbaceous vegetation. Forests, the third largest land cover type in Senegal, are primarily concentrated in the southern parts of the country, such as in Kédougou, Ziguinchor, and Sedhiou. The built-up areas which occupy 0.5 percent of total land cover are mainly concentrated in Dakar.

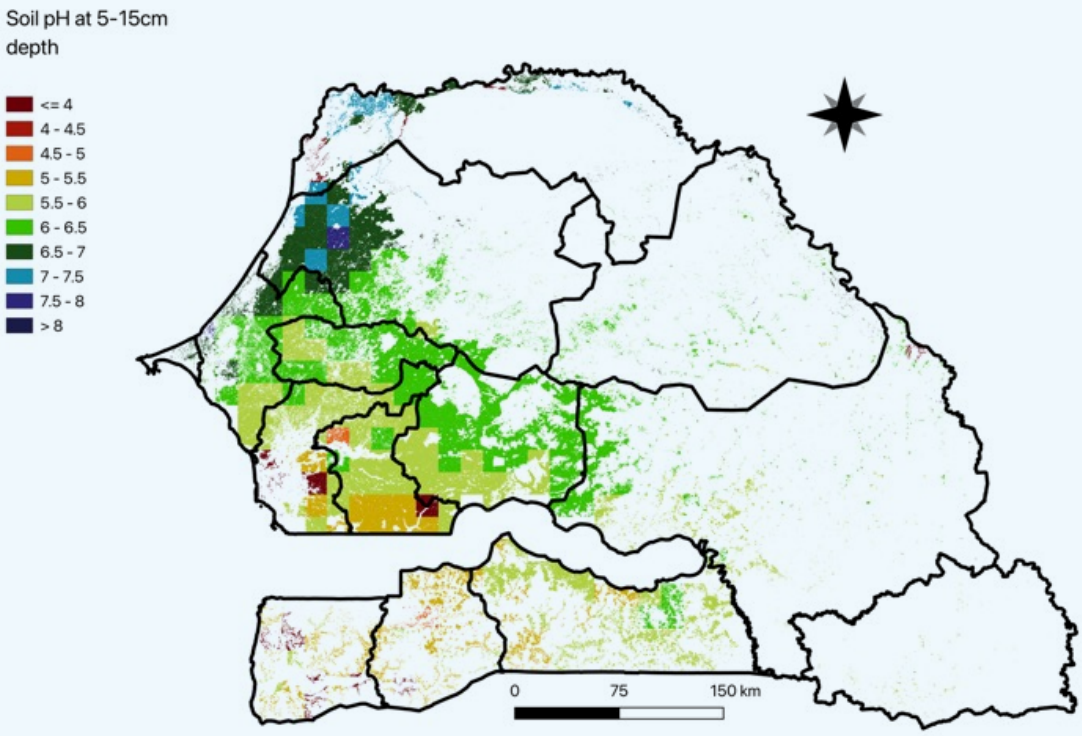
5. Soil Properties

5.1. Soil pH

This section presents the results of analysis of cropland soil pH at 5-15 cm in Senegal. The analysis sought to determine the acidity or alkalinity of the cropland soils, as this is a critical factor in plant growth and nutrient uptake. Data were sourced from the SoilGrids dataset and the Copernicus Global Land Cover platform.

The analysis showed that cropland soils in Senegal ranged from strongly acidic (pH<4) to slightly alkaline (pH=7.7), with a mean pH of 6. The pH values of cropland soils varied significantly among Senegal's different regions. The lowest pH values (strongly acidic and moderately acidic soils) are in Senegal's southern regions while neutral soils and moderately alkaline soils are generally observed in Senegal's central and northern regions.

Figure 10: Soil pH of croplands at 5-15 cm depth in Senegal

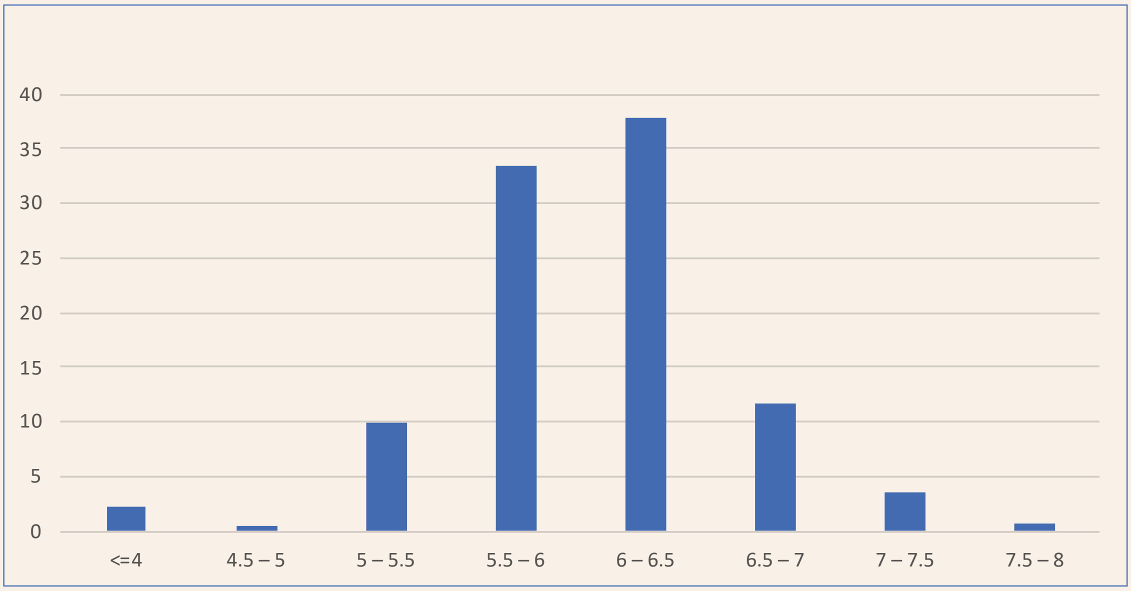


Source: Data processing and map by authors.

Figure 11 represents the percentage of each soil pH range for Senegal's total cropland area based on the SoilGrids dataset and the Copernicus Global Land Cover platform. Most cropland soils in Senegal are acidic as 83.14 percent have a pH between 5.5 and 7. This pH is favorable for some of the major crops found in Senegal such as rice and groundnuts (Shamshuddin et al. 2017) (Halim et al. 2018). Soils with a pH in this range encourage the solubility of minerals and nutrients (such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn)) therefore making them available to plants (Queenland Government 2022) (SUNY college of Environmental Science and Forestry n.d.). Only 15.92 percent of Senegal's croplands have a pH between 6.5 and 8, which is a good range for sorghum and millet growth (Shamshuddin et al. 2017).

Crucially, 16.86 percent of Senegal's croplands have a pH that is less than 5.5 or greater than 7. These pH values cause aluminum toxicity (Fageria and Nascente 2014) (Queenland Government 2022) and nutrient unavailability (Shamshuddin et al. 2017) for rice and peanuts, affecting the growth and yields of these crops. Moreover, 84.08 percent of Senegal's croplands are unfavorable for the growth of sorghum and millet due to these same reasons.

Figure 11: Cropland distribution by soil pH classes at 5-15 cm depth in Senegal

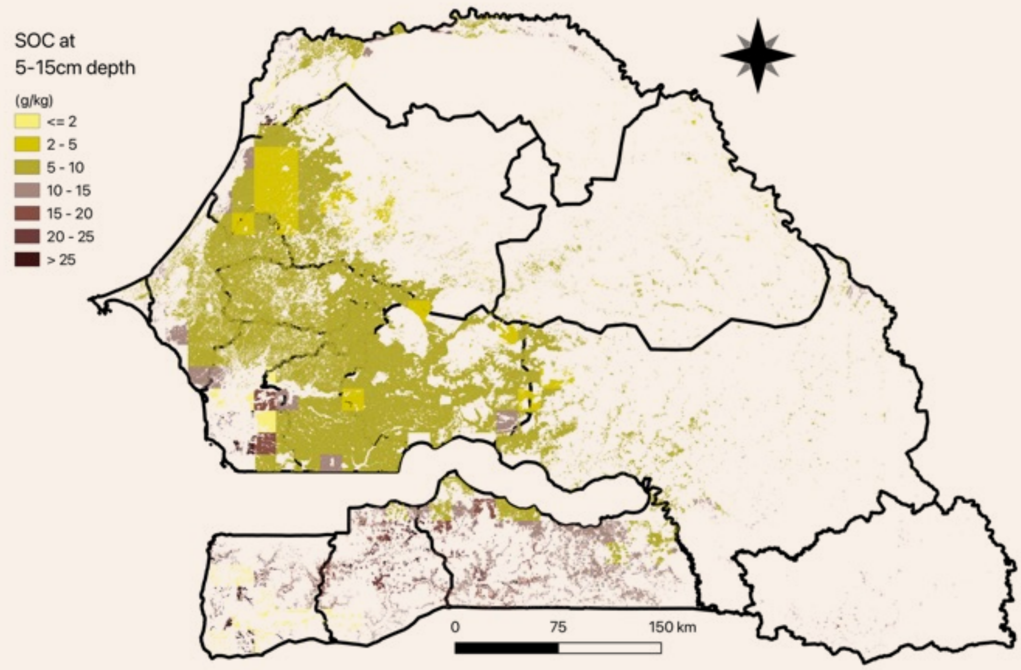


Source: Data processing by authors.

5.2. Soil Organic Carbon

This section uses data on cropland soils for Senegal's different regions from the Copernicus Global Land Cover platform. The objective was to assess the amount of soil organic carbon (SOC) found at 5-15 cm depth in the country's cropland soils using the SoilGrids dataset. The results showed significant variations in SOC levels across the country, with southern regions having higher levels than central and northern regions. In Senegal, SOC quantities vary between 0 and 49.3 g/kg (0 – 4.93 percent) with a mean value of 7.59 g/kg (0.76 percent).

Figure 12: Soil organic carbon at 5-15cm depth in Senegal

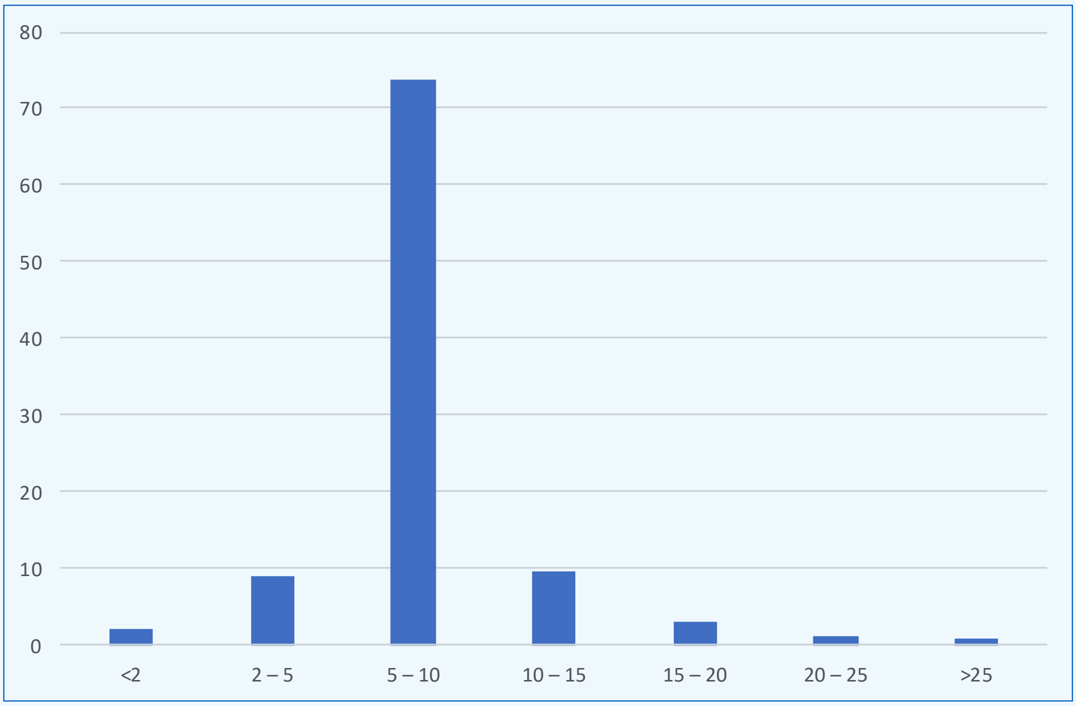


Source: Data processing and map by authors.

Figure 13 represents the percentage of each SOC range (in g/Kg) encountered over Senegal's total cropland area based on the SoilGrids dataset. The analysis shows that 97.65 percent of Senegal's cropland soils have an SOC value of less than 20 g/kg (2 percent). These low SOC values represent a decrease in the soil's physical resistance and resilience (Rumpel et al. 2020) which may affect soil fertility and decrease potential crop production. This also means that the soil sequesters only a small amount of atmospheric carbon.

The 2.35 percent of cropland soils with an SOC value of more than 20 g/kg (2 percent) are more favorable to physical, chemical, and biological processes in the soil (Blanco-Canqui et al. 2013). In this case, soil fertility (Rumpel et al. 2020) and porosity (Johannes et al. 2017) will tend to increase, consequently resulting in better crop production. This also means that more atmospheric carbon is sequestered in these soils, hence they contribute more to climate change mitigation (Rumpel et al. 2020) (Blanco-Canqui et al. 2013).

Figure 13: Cropland distribution by soil organic carbon at 5-15cm depth in Senegal



Source: Data processing by authors.

6. Drought Index

Drought is a natural phenomenon marked by prolonged, dry weather conditions which cause intense water shortages (World Bank 2019) and can have negative impacts on lives, properties, and activities (World Bank 2019). In parts of West Africa, drought hazards have contributed to the scarcity of natural resources and low yields, resulting in crop failures, food price inflation, hunger, and malnutrition (United Nations Office for Disaster Risk Reduction (UNDRR) 2021). (World Bank 2019) identified four categories of droughts: meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought. We oriented our analysis to agricultural drought in general, which is determined by measuring soil moisture. We used the modified vegetation water supply index (MVWSI) developed by (WU and LU 2016) to design an index for agricultural drought risk assessment. (WU and LU 2016) showed that use of MVWSI can eliminate regional and seasonal features at a large scale by introducing the relative normalized difference vegetation index (RNDVI) and the relative land surface temperature (RLST). The RNDVI is defined as the relative difference of the normalized difference vegetation index (NDVI) observed in the current year over the average normalized difference vegetation index over the last 20 years, termed $\overline{NDVI}$.

As RNDVI is unstable for exceedingly small values of , only values of ≥ 0.1 are considered, and RNDVI equals unity. The RLST is defined in the same way.

$$RLST = \frac{LST}{\overline{LST}}$$

Both Land Surface Temperature (LST) and $\overline{LST}$ are considered in degrees Celsius. RLST being unstable for exceedingly small values of $\overline{LST}$, only values of $\overline{LST}$ ≥10° C are considered, and RLST equals unity otherwise.

And finally, MVWSI is defined as the ratio of the relative normalized difference vegetation index (RNDVI) over the square of relative land surface temperature (RLST).

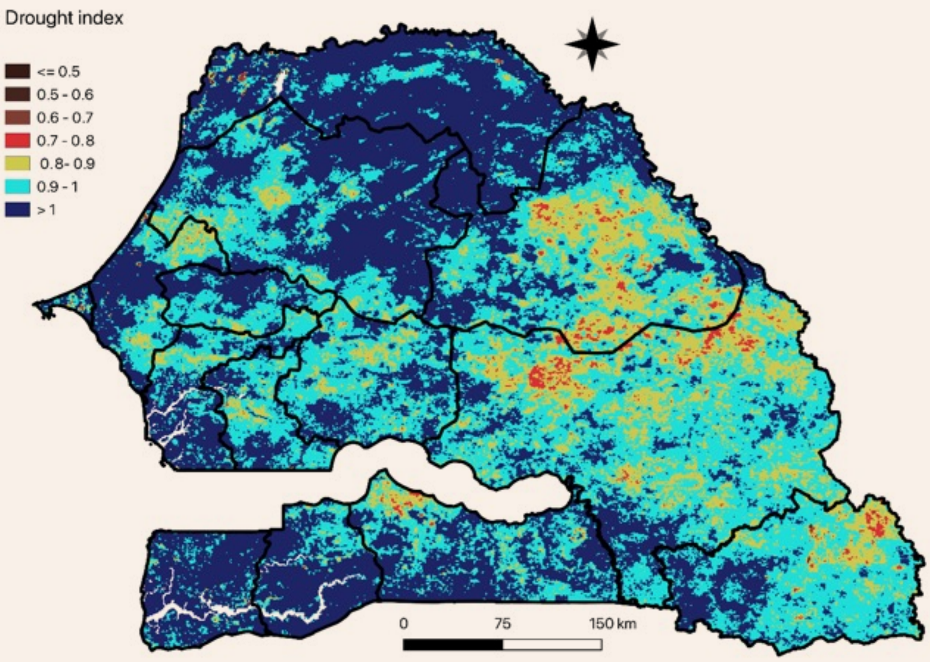
$$MVWSI = \frac{RNDVI}{RLST^2}$$

Wu and Lu (2016) justified the choice of $RLST^2$ instead of RLST by the still smallness of RLST values, tests on the study have proven that the square is always more significant than the other power.

According to Wu and Lu, values of MVWSI between 0 and 1 highlight the drought-prone area. The smaller the MVWSI value, the less vegetation water supply and the more pronounced the drought is. Regions having an MVWSI greater than unity do not suffer from drought.

This study focused on determining West Africa's MVWSI index in 2021. We collected 2001-2021 data on NDVI and LST. The averages of 2021 data are considered to be current year averages while those from 2001 to 2020 are considered to be long-term averages for the last 20 years. Figure 14 presents the MVWSI map produced.

Figure 14: Senegal's drought index, 2021



Source: Data processing and map by authors.

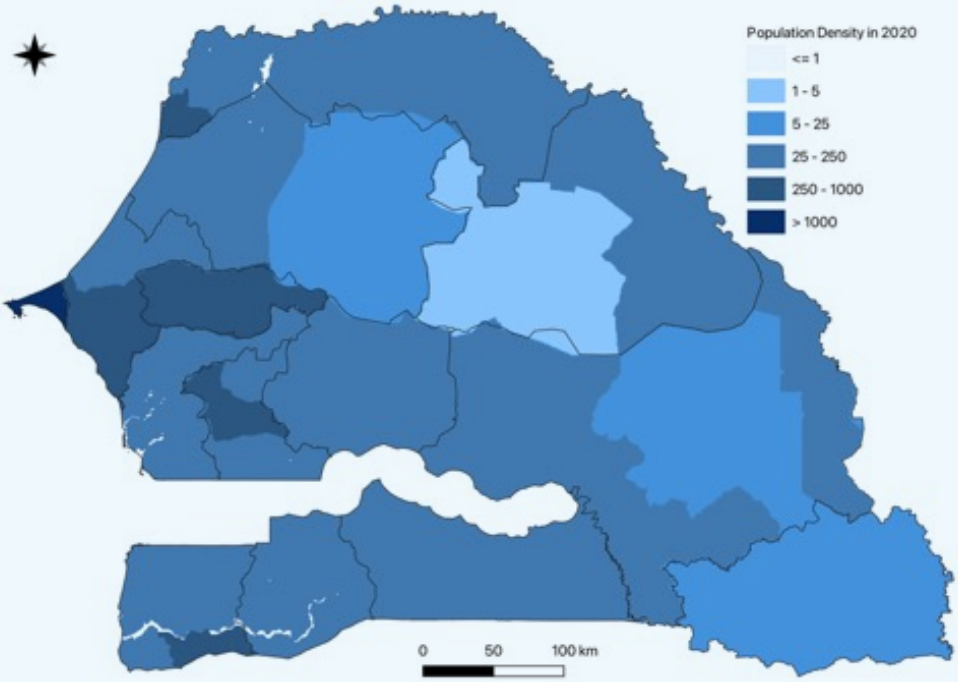
Senegal's eastern regions (Matam, Tambacounda and Kédougou) are more exposed to agricultural drought hazards. Moreover, the fact that agriculture is predominantly rainfed and contributes significantly to the country's gross domestic product (GDP) means that these regions and the country as a whole, are particularly vulnerable to drought impacts. Some of the dominant crops grown in these regions, such as sorghum and millet, are drought tolerant (Abreha, Enyew, and Carlsson 2022) (Tadele, Shanker, and Shanker 2016) and can therefore strengthen adaptation strategies under certain conditions. Other important crops in these regions such as maize are drought sensitive (McMillen et al. 2022) and susceptible to stress and failure (McMillen et al. 2022). This may lead to food price inflation, hunger, and malnutrition (United Nations Office for Disaster Risk Reduction (UNDRR) 2021). Drought is less severe in Senegal's central regions of Kaolack and Kaffrine. Groundnuts, the dominant crop in these regions, can withstand moderate to severe drought conditions for a limited time, but prolonged drought periods can negatively impact their growth and yields. Finally, Senegal's northern and southern regions are moderately affected or free from drought.

7. Population Density

The population density adjusted from the Gridded Population of the World, Version 4 (GPWv4), consists of estimates of human population density (number of people per square kilometer) based on counts consistent with national censuses and population registers concerned with relative spatial distribution. These data are adjusted to match the 2015 Revision of the United Nation's World Population Prospects (UN WPP) country totals, for the years 2000, 2005, 2011, 2015, and 2020. A proportional allocation gridding algorithm using approximately 13.5 million national and sub-national administrative units, assigned UN WPP-adjusted population counts to 30 arc-second grid cells. The data files were produced as global rasters at 30 arc-second (~1 km at the equator) resolution. Density rasters were created by dividing the UN WPP-adjusted population count raster for a given target year by the land area raster.

In this section, we focus on Senegal's population density in 2020 with data extracted from the GPWv4 platform. The map below illustrates how the population is distributed across the country.

Figure 15: Population density (number of people per) in Senegal, 2020



Source: Data processing and map by authors.

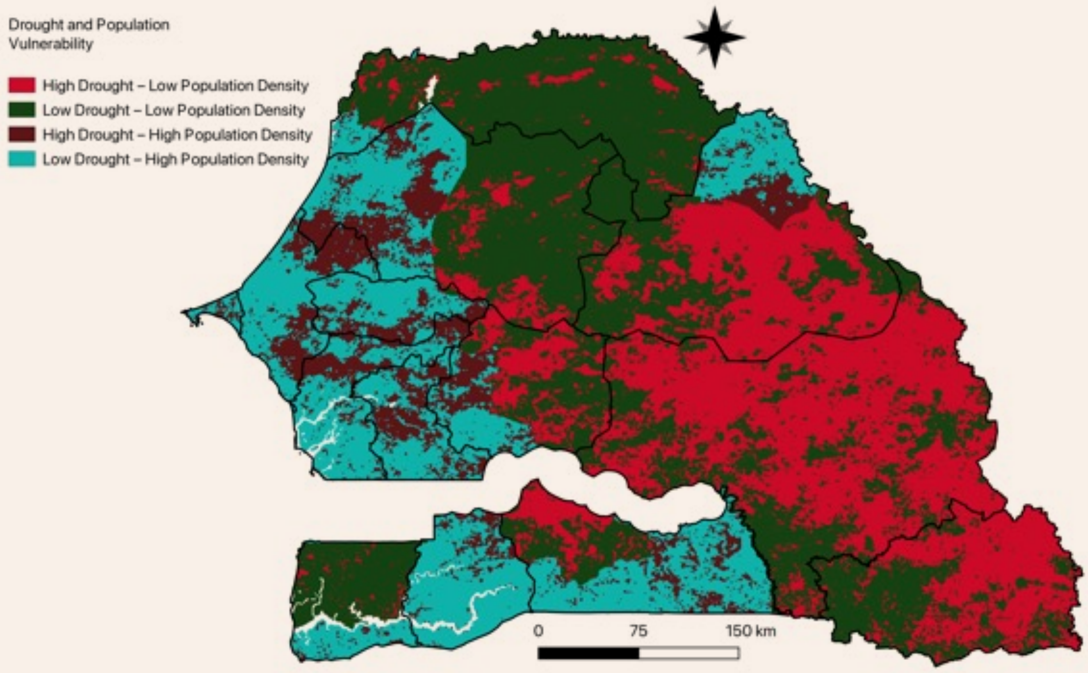
The map shows that the highest population densities are found in the western part of the country, particularly in Dakar which has a population density of more than 1,000 people per square kilometer. However, significant population densities ranging from 25 to 1,000 people per square kilometer can also be seen in most areas, especially in the western parts of the country. In contrast, lower population densities are observed in the central and eastern regions such as parts of Louga, Tambacounda, and Kédougou. The western part of Matam has the lowest population density which is less than five people per square kilometer.

8. A Climate Risk Typology based on Drought Index and Population Density

Figure 16 shows a typology of Senegal's regions based on their exposure and vulnerability to climate risks. Exposure is measured by the drought index which is estimated using the formulas detailed in section six while population density determines vulnerability. We assume that regions with high population densities are more vulnerable to climate risks as competition for resources and social services is expected to intensify.

Eastern Senegal has several regions that are highly exposed to drought conditions such as Matam, Tambacounda, and Kédougou. However, these areas also have low population densities, meaning that while droughts may be more severe, relatively fewer people are affected. The same pattern is observed in some parts of Kolda. The western central areas in Senegal including parts of Louga, Thies, Diourbel, Kaolack, Kaffrine, and Fatick have higher population densities and more people are affected by drought. These areas have higher vulnerability scores as they are more densely populated and greatly affected by drought. Senegal's northern regions, including Saint Louis and parts of Louga, as well as Ziguinchor in the south, are more resilient to drought. These areas experience low incidence of drought or are drought-free.

Figure 16: Typology of micro-regions based on drought and population density



Source: Data processing and map by authors.

9. Conclusion

Overall, climate change significantly impacts Senegal's climatic variables, with potentially negative impacts on human well-being, the environment, and economic development. Precipitation patterns in Western Africa are also changing, with some areas experiencing increased rainfall, while others are becoming more arid. This has significant implications for agriculture and food security, as well as the availability of water resources.

It is essential to implement measures to adapt to these changes and reduce greenhouse gas emissions, so as to mitigate their long-term impacts. Senegal's climate largely influences the country's economy and the overall well-being of its people, especially in terms of agricultural production, water resources, and human health. The country has a tropical climate evident in the high temperatures and distinct dry and rainy seasons with unpredictable rainfall patterns. Senegal is not impervious to the effects of climate change which threaten the country's water resources, agricultural activities, and economic growth. Recent climate-related challenges, such as more frequent and severe droughts and floods, have seriously damaged the country's food security situation and its rural communities.

Senegal has implemented several practical strategies and policies to combat the challenges posed by climate change. These include improving water management, promoting agricultural practices, and strengthening warning systems for weather-related catastrophes. These endeavors aim to bolster the country's resilience to climate change. To safeguard its people, natural resources, and economy for future generations, Senegal must prioritize climate change mitigation and adaptation measures. Addressing the climate variables examined in this report through concerted and sustained efforts is critical, as the country's development and well-being hinge on effectively tackling the challenges posed by climate change.

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AKADEMIYA2063 | Kicukiro/Niboye KK 341 St 22 | 1855 Kigali-Rwanda

+250 788 318 315 | +221 33 869 28 81

kigali-contact@akademiya2063.org | dakar-contact@akademiya2063.org

www.akademiya2063.org

@AKADEMIYA2063