Climate Vulnerability Assessment for selected crops in Senegal

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Contents

Abstract

The Adaptation and Valorization of Entrepreneurship in Irrigated Agriculture (AVENIR) project aims to improve the socioeconomic well-being and resilience of farming households in the regions of Sedhiou and Tambacounda, Senegal. The project focuses on smallholder-irrigated systems through promotion of climate-adapted crops, smallholder irrigation and climate-smart agricultural technologies, particularly for women and young people. AVENIR seeks to promote crop diversification through the integration of rice, agroforestry,and horticulture. In the Tambacounda Region, in the Goudiry and Tambacounda Departments, the project will focus on activities along the rice and baobab value chains. In the Sédhiou Region, in the departments of Bounkiling and Goudomp, AVENIR will center on the rice, mango, and cashew value chains. Other crops prioritized for the two regions are ditakh, madd, onion,okra, and pepper.

The vulnerability assessment for the selected nine crops in Senegal is based on their sensitivity to change, their exposure, and their adaptive capacities. The ultimate purpose of this study is to assess if future climate have a neutral, negative or positive (no change/decrease/increase) impact on crop productivity, and to identify regions of concern and opportunities for climate change adaptation. We use the Maxent ecological models under intermediate and high-emission climate scenarios – Representative Concentration Pathways (RCPs) 4.5 and 8.5, respectively – to assess the sensitivity of the nine crops (rice, mango ,baobab, cashew, madd, ditakh, okra, onion and pepper) to climate change.

To produce a crop-specific vulnerability index and a final accumulative score, we combined the components of vulnerability using equal weighting. We also map the hotspots of climate change vulnerability and identify the underlying driving indicators. In Senegal, all the nine crops studied are most vulnerable in the southeastern regions, especially Tambacounda, Kaffrine, Sedhiou, Kolda, and Kedougou regions. More so, there is high vulnerability for baobab trees, ditakh, and madd to the north, and cashews, okra, mangoes, onions, peppers, and rice to the northeast. This study highlights how the adaptive capacity of the farming population can be enhanced by augmenting access to education and health care, improving nutrition, and developing infrastructure for marketing, transportation, and irrigation.

1. Introduction

Senegal is located in western Africa on the Atlantic Coast between the latitudes of 12°30° and 16°30°N and the longitudes of 11°30° and 17°30°W. The southern region of Senegal has a tropical climate, while the northern region lies in a sub–tropical, semi–arid belt called the Sahel (Mcsweeney et al., 2008). The southern areas are situated in Sudan, a West African climatic zone that encompasses the transition between the dry Sahel and the very moist Guinean and equatorial coastal zone. Rainfall is mainly controlled by the movement of the Intertropical Convergence Zone (ITCZ) (Lucio, 2012)a high reduction (about 70%. The movement of the ITCZ determines the onset and duration of the rainy season (Salack et al., 2011)the number of rainy days and daily rainfall types, dry spells frequency of occurrence, onset/cessation/length of rainy season, sowing dates, and the duration of the cropping period, are investigated at local (individual sites. For example, the south has more rainy days and a longer rainy season than the drier north.

Temperatures in Senegal exhibit an east-to-west gradient, such that inland temperatures are normally higher than along the coastline, with the highest temperatures occurring in the northeastern parts of the country (Fall et al., 2006). In the hottest season, the highest temperatures reach an average of 35°C, while the cooler coastal regions experience temperatures between 25°C to 28°C (Mcsweeney et al., 2008). In the cooler seasons, average temperatures can fall below 25°C at the coast but still climb to 30°C in the east (Fall et al., 2006).

Rainfall begins in the southeast around May or June, and spreads northwest throughout the summer months (Marteau et al., 2009). Most of Senegal's annual rainfall is received from June through September. August accumulates the highest amount of rainfall, followed by September, July, and June (Camberlin and Diop, 2003). The dry season, on the other hand, lasts for about six months in the south and eight months in the north. The most seasonal rainfall is received in the southern parts of the country, measuring approximately1000 mm during the rainy season, while the northern parts are drier, accruing less than 400 mm (USAID, 2017, 2015). The rainy season ceases with the migration of the ITCZ to the south around October (Nicholson, 2018).

The agricultural sector of Senegal contributes about 17% of the country's gross domestic product (GDP), employing more than 70% of the workforce (World Bank, 2018). Senegal is one of the most stable and promising countries in West Africa with great potential to increase its agriculture-led economic growth (USAID, 2015). However, a large portion of Senegal's land mass lies within the Sahel, which is arid and highly prone to droughts (Mcsweeney et al., 2008). This location makes rain-fed agricultural production highly variable, a situation that climate change is exacerbating (D 'Alessandro et al., 2015).

Senegal is divided into six agroecological zones (Figure 1) based on biophysical and socioeconomic characteristics (Alessandro et al., 2015; CIRAD, 2015). Moving from north to south, these are the following:

1. The Senegal River Valley is characterized by alluvial plains and sandy uplands with irrigated rice production; it covers a surface area of 9,658 km^2. Rain-fed agriculture in this area is almost nonexistent, and most agricultural production occurs with irrigation (Alessandro et al., 2015). Although salinity is a problem in some areas, much of the land has high fertility levels because of regular flooding and siltation.

2. The Niayes on the Atlantic coast features a temperate climate and produces fruits and vegetables (CIRAD, 2015). This 10km strip occupies 2,759 km^2. Niayes is a densely populated area and faces challenges including soil and water salinity and coastal erosion (Alessandro et al., 2015).

3. The sylvo-pastoral zone of north-central Senegal supports extensive livestock production and covers 55,561 km^2 (CIRAD, 2015).

4. The Groundnut Basin of south-central Senegal is a zone of savannah dominated by groundnut and millet production (CIRAD, 2015). It covers an area of 46,367 km^2 and is densely populated. Ecosystem degradation and depletion of land resources, mainly soil fertility and timber resources, affect the area (Alessandro et al., 2015). Because of upland soil acidification and lowland salinity, soil regeneration has declined.

5. Eastern Senegal is characterized by savannah with trees. Its agricultural production involves primarily cotton and livestock. It covers an area of 51,958 km² and is subject to rampant rural poverty because of extreme population pressure on natural resources, despite its robust agro-pastoral potential (Alessandro et al., 2015).

6. The Casamance is characterized by forests and savannah with trees (CIRAD, 2015). Its agricultural production includes mainly rain-fed rice along with diverse other crops. With a total surface area of 28,324 km², it is divided into three zones—lower, middle, and upper. The region faces challenges such as lowland soil acidification, water erosion, a loss of forest diversity, increased soil salinization, iron toxicity, and acute mangrove degradation (Alessandro et al., 2015).

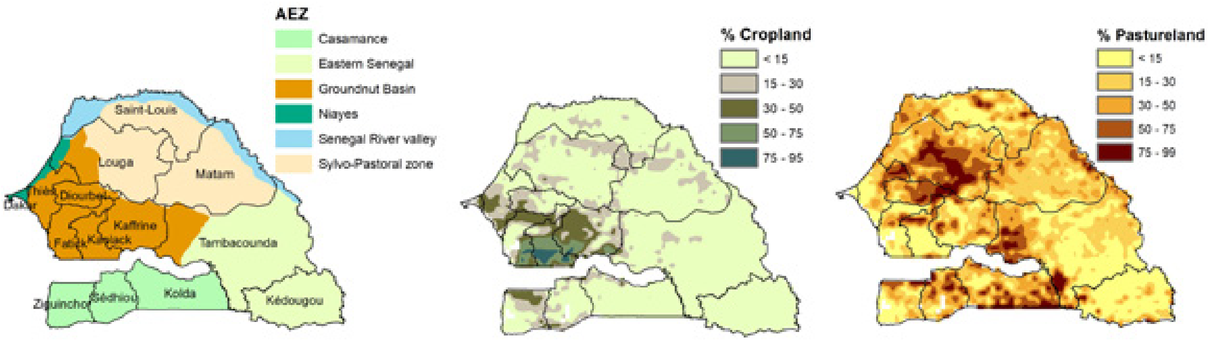

Figure 1: Agroecological zones of Senegal (left), cropped areas (center), and areas with pastures (right). Data for the left panel were adapted from the Directorate of Water, Forests and Hunting Conservation, and the center and right panels were taken from Ramankutty et al., 2008.

The topography of Senegal is generally flat with rolling sandy plains, but rises to hills in the southeast. Most areas have elevations of less than 100 m above sea level. Senegal encompasses over 19 million ha of land, of which only about 20% or 3.9 million ha are suitable for arable crops. The rest comprises undeveloped bush and arid areas used for livestock grazing (Alessandro et al., 2015). Around 40% of the arable land is constantly cultivated, although 10% receives less than 500 mm of rainfall per year, which limits crop production. Only 10% of the cultivated land is under irrigation, mainly along the Senegal River and in the Casamance (Peterson et al., 2006). This challenge aligns with the goal of the AVENIR project, which aims to improve access for irrigation technologies and improve the governance and management of water resources, working with government, civic groups and market actors in Sedhiou and Tambacounda regions.

Population increases have led to land pressure (Place and Otsuka, 2000), which in turn has brought about soil degradation and declining soil fertility due to many years of unsuitable agricultural practices such as tillage practices, mono-cropping, and incorrect use of chemical inputs (Doso Jnr, 2014; Sow et al., 2015). Soils in most areas have low percentages of clay and organic matter and therefore low cation exchange capacities, resulting in increased vulnerability to nutrient depletion (Mahé et al., 2002; Matlon, 1987).

The major crops grown in Senegal are groundnuts and millet, which account for approximately 75% of the cropped area. Other crops such as maize, rice, sorghum, cowpeas, and cotton are also cultivated. Vegetables account for less than 1% of the cropped area (Elberling et al., 2003)overgrazing and lack of agricultural management influence the amount, quality and turnover of soil organic carbon (SOC. Because food production does not the meet domestic demand, the country imports rice and wheat (Diagne et al., 2013)several initiatives to upgrade the rice value chain have emerged in the private sector. However, the major constraint private investors are currently facing is the insufficient supply of Senegal River Valley (SRV. Senegal exports cotton, groundnut oil, and horticultural products, mainly green beans, tomatoes, and mangoes (D'Alessandro et al., 2015).

Crop production in Senegal falls into several categories: subsistence smallholders, commercial smallholders, and pure commercial producers (D'Alessandro et al., 2015). Subsistence smallholders produce food mainly for consumption with occasional surplus for sale, while commercial smallholders produce cash crops for sale and some food crops for their own consumption.

About 90% of the rural population of Senegal are involved in livestock production, which accounts for 30% of the country's GDP (Diagne et al., 2013)several initiatives to upgrade the rice value chain have emerged in the private sector. However, the major constraint private investors are currently facing is the insufficient supply of Senegal River Valley (SRV. The livestock they keep includes cattle, goats, and sheep. The cattle provide plowing power which is used in cropped lands (D'Alessandro et al., 2015).

Senegal is highly vulnerable to risks associated with climate change (USAID, 2017). Years of erratic rainfall patterns and rising sea-levels have led to increased soil erosion, agricultural soil salinization, and the destruction of infrastructure. Droughts and floods associated with climate change have increased the country's vulnerability to food security (Salimata, 2020). In the Senegal River Valley, the Niayes, and the Casamance, agriculture and fisheries are the main economic activities, and they are highly vulnerable to reductions in rainfall, coastal erosion, salt water intrusion, and flooding (Salimata, 2020).

Photo: © (CCAFS).

2. Climate Vulnerability Assessment methodology

The methodology used to prepare this report hinges on the conceptual framework of climate-related risk from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) Working Group II to explore the potential consequences of climate change for agriculture and food security (Adger, 2006; O'BRIEN et al., 2007; Sharma and Ravindranath, 2019). The IPCC defines vulnerability as "the extent to which a natural or social system is susceptible to sustaining damage from climate change impacts, and is a function of exposure, sensitivity and adaptive capacity". The impact of climate change on agriculture and livelihoods therefore can be conceptualized as the aggregation of these components (Foden et al., 2013).

Exposure refers to the amount of climate variation to which a system could be subjected by hazards. Sensitivity, meanwhile, is the degree to which the system could be affected by that exposure. Finally, adaptive capacity is the ability to adjust, cope with, or benefit from expected climate variations. The analysis was implemented by obtaining indicators relevant to Senegal for each dimension of vulnerability. These indicators were then aggregated as shown in equation 1 below to compute the vulnerability of each crop and administrative unit or arrondissement.

In the vulnerability framework we use here, the vulnerability of each crop is calculated using crop-specific sensitivities, exposure to natural hazards, and a series of indicators of adaptive capacity (equation 1), and the results are then summed up to obtain overall vulnerability (Parker et al. 2019)a need exists to understand and prioritise at the sub national scale which areas and communities are most vulnerable. The purpose of this study is to develop a robust, rigorous and replicable methodology that is flexible to data limitations and spatially prioritizes the vulnerability of agriculture and rural livelihoods to climate change. We have applied the methodology in Vietnam, Uganda and Nicaragua, three contrasting developing countries that are particularly threatened by climate change. We conceptualize vulnerability to climate change following the widely adopted combination of sensitivity, exposure and adaptive capacity. We used Ecocrop and Maxent ecological models under a high emission climate scenario to assess the sensitivity of the main food security and cash crops to climate change. Using a participatory approach, we identified exposure to natural hazards and the main indicators of adaptive capacity, which were modelled and analysed using geographic information systems. We finally combined the components of vulnerability using equal-weighting to produce a crop specific vulnerability index and a final accumulative score. We have mapped the hotspots of climate change vulnerability and identified the underlying driving indicators. For example, in Vietnam we found the Mekong delta to be one of the vulnerable regions due to a decline in the climatic suitability of rice and maize, combined with high exposure to flooding, sea level rise and drought. However, the region is marked by a relatively high adaptive capacity due to developed infrastructure and comparatively high levels of education. The approach and information derived from the study informs public climate change policies and actions, as vulnerability assessments are the bases of any National Adaptation Plans (NAP.

$$Overall\ vulnerability = \sum_{i=1}^{n}[\frac{1}{2}\left(\left(\frac{1}{2}\left(\frac{Growing\ area_i}{Total\ area} * S_i + E_i\right)\right) - AC\right)]$$

[Equation 1]

Where *i* denotes each crop; *Growing area* refers to the extent of suitable area for the crop *i*; *Total area* pertains to all crops; S_i is the sensitivity of the value chain *i*; E_i represents the exposure of each crop; and *AC* is the adaptive capacity.

Sensitivity index, S_i, was determined by computing the difference between the future and current crop suitability followed by normalizing the values to a scale ranging from -1 and 1. Exposure indices, E_i was determined by obtaining the variables representing the value chains exposure such as aridity, flood etc. and extracting the values for each arrondissement. The resulting values were then normalized to a scale ranging from 0 and 1. Adaptive capacity, *AC* on the other hand was determined by obtaining the variables that enhance the adaptive capacity of Senegal such as literacy rate, health, poverty etc. and extracting the values for each arrondissement. The resulting values were also normalized to a scale ranging from 0 and 1. Crop suitability was modelled for nine selected crops: baobab, cashew, ditakh, madd, mango, onion, okra, pepper, and rice, using the Maxent suitability model package in R Statistical software (Figure 2). These crops were selected from a value chain study conducted for the AVENIR project in February-March 2020, which identified these as the most promising crops for socio-economic progress in the regions of Tambacounda and Sedhiou. To obtain one index for each variable in the equation e.g., one index for *AC* in calculating total vulnerability for a specific crop, all indices were added and normalized to a scale between 0 and 1.

3.0 Results

3.1 Crop suitability

Crop suitability determines the effectiveness of a specific area for the production of a particular crop within a defined system of agricultural production based on agro-climatic conditions related to temperature and moisture, and on agro-edaphic conditions pertaining to soils and landforms (Kassam et al., 2012; Nisar Ahamed et al., 2000)1976. A framework for land evaluation (Soils Bulletin No. 32.

We carried out a Maxent suitability model using available crop presence data and gridded climate data for current and future scenarios pertaining to the 2030s and 2050s, and for two Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5. RCPs describe various climate futures whose likelihood of occurring depends upon the volume of anthropogenic greenhouse gases (GHG) emitted over the years. RCP 4.5 is an intermediate scenario premised on the employment of a range of technologies and strategies for reducing GHG emissions. RCP 8.5 is a high-end scenario characterized by increasing GHG emissions over time. Our crop presence data derives from the Global Biodiversity Information Facility public database (http://www.gbif.org). The variables we used include climate data with bio-climatic variables relating to temperature in addition to slope, soil texture, soil pH, and waterlogging. We obtained current climate data from WorldClim 2.0 (Fick and Hijmans, 2017), whereas we downloaded future climate data from CCAFS-Climate (Navarro-Racines et al., 2020)we present a global database of future climates developed by applying the delta method –a method for climate model bias correction. We performed a technical evaluation of the bias-correction method using a 'perfect sibling' framework and show that it reduces climate model bias by 50–70%. The data include monthly maximum and minimum temperatures and monthly total precipitation, and a set of bioclimatic indices, and can be used for assessing impacts of climate change on agriculture and biodiversity. The data are publicly available in the World Data Center for Climate (WDCC; cera-www.dkrz.de. We calculated slope data from a digital

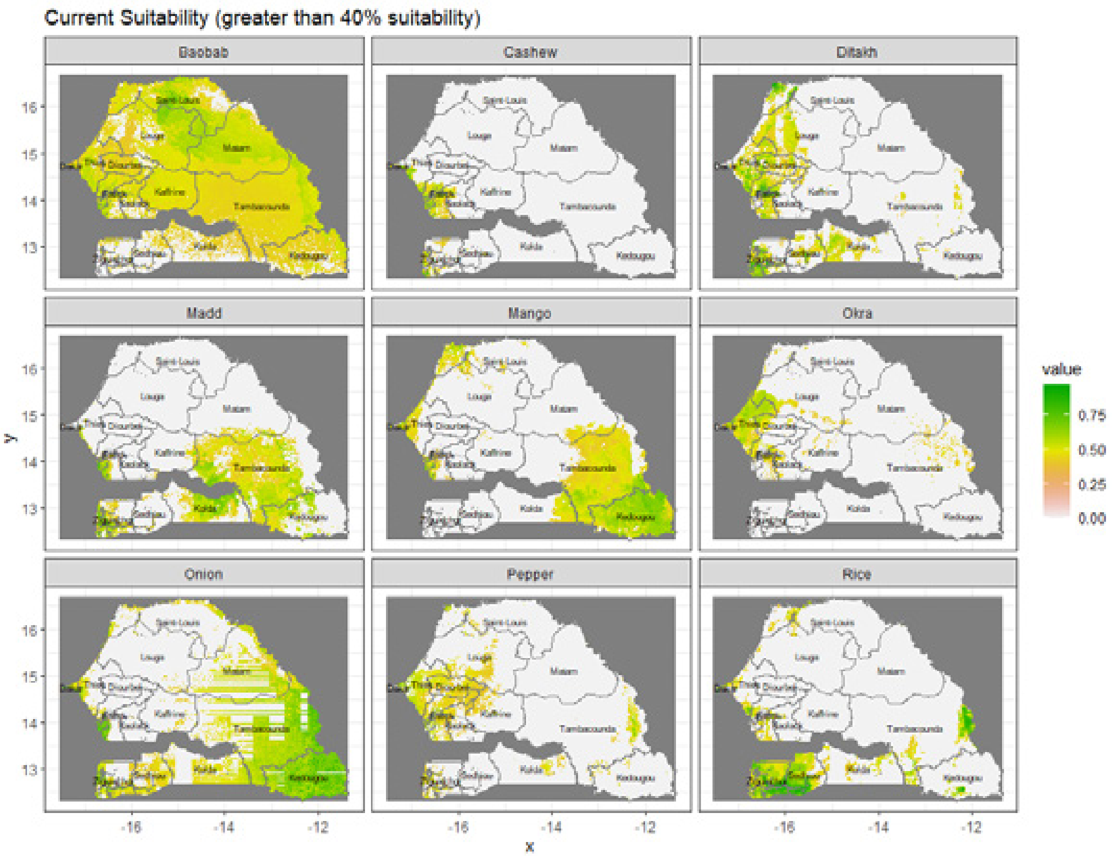

Figure 2: Current crop suitability in Senegal, showing the areas that are 40% suitable and above

elevation model obtained from the United States Geological Survey's EarthExplorer, and determined soil texture and pH from the International Soil Reference and Information Centre World Soil Information database. Finally, we collected information about waterlogging from the United Nations Food and Agriculture Organization (FAO) Global Assessment of Soil Degradation (Fischer et al., 2008).

We present this information in two ways: (1) the current (baseline) magnitude of suitability; (2) the magnitude of change under future climate projections. The magnitude of change reflects whether crop suitability increase or decrease relative to the baseline period. In the following section, we show agreement maps that rank the current suitability from zero, meaning areas projected to be climatically unsuitable for production of the crop, to one, where the area presents greatest climatic conditions suitable for crop production.

The current suitability of the selected crops in the project areas, show that, baobab, mango madd and onion have high suitability in Tambacounda while ditakh, onion and rice have high suitability in Sedhiou. Cashew, show very low suitability in both Sedhiou and Tambacounda with Okra, pepper and madd showing very low suitability in Sedhiou. In Tambacounda however, madd shows high suitability while okra and pepper have pockets of high suitability spread out in the region. Rice in Tambacounda is suitable along the Senegal river to the east as well as to the south.

3.2 The sensitivity of value chains to climate change

Sensitivity expresses the relationship between human-induced emissions and the temperature changes that will result from these emissions. It is the amount of warming caused by increases in atmospheric carbon dioxide (CO_2) (Hawkins and Forster, 2019). Frequently, sensitivity is defined as the change in temperature resulting from a doubling of the concentration of CO_2 in the atmosphere. In this case, we calculated sensitivity using crop suitability such that we understood sensitivity as the change in suitability. Therefore, we computed the difference between the future and current crop suitability.

We analyzed the sensitivity of all crops under future climate projections for 2030s under RCP 4.5 (Figure 3). All the selected crops experience some degree of sensitivity, either an increase or decrease. Increasing sensitivity infers that climate change will affect productivity patterns for the crop. The change in suitability maps range from -1 meaning areas with 100 percent crop suitability loss, to +1 representing areas where there is 100% suitability increases. By the 2030s under RCP 4.5, mangoes, cashews, okra, and peppers are the most sensitive crops, while onions and rice are least sensitive. In this scenario, increasing suitability is strongly exhibited by baobabs, ditakh, and madd in the north, by cashews in the northeast, and by peppers in the northeast and southeast. Decreasing suitability is likely for mangoes in the southeast and okra in the western regions of Senegal.

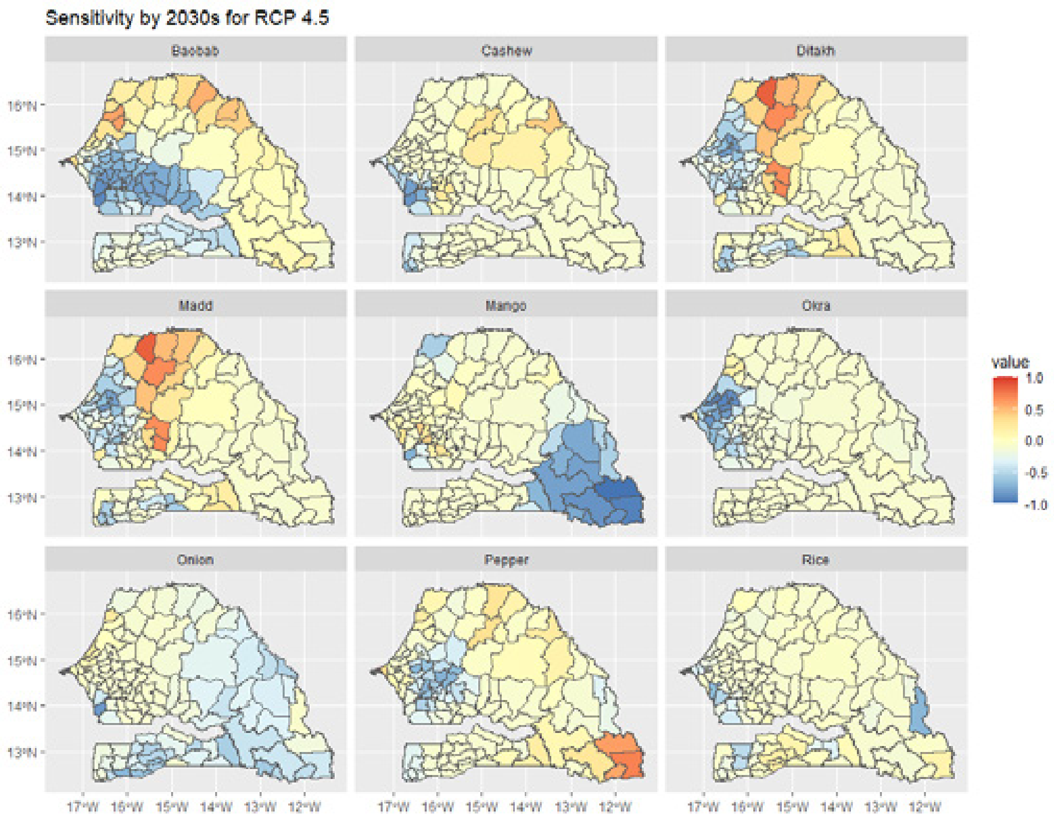

Figure 3: Changes in suitability for selected value chains by the 2030s for RCP 4.5. 1.0 denotes increasing suitability and -1.0 a loss in suitability.

For most of the selected crops, climate change impacts will negatively affect the western parts of Senegal. In the east, mangoes and onions undergo a loss in suitability. The northern areas, however, will become more suitable for almost all nine crops. Looking at our project areas, there is a likelihood for a decreasing suitability in Mango and onion in Tambacounda with a slight increase in suitability for baobab. On the other hand, there is a likelihood for a decreasing suitability in baobab, ditakh, madd and onion in Sedhiou which could lead to a decrease in production by 2030 for RCP 4.5. Pepper and rice however, show a slight increase in suitability by 2030 for RCP4.5.

Results for RCP 8.5 for the 2030s and RCP 4.5 and 8.5 for 2050s are shown in the supplementary figures in the Annex. In general, the results for RCP 8.5 are consistent with RCP 4.5 for the 2030s. However, most crops such as baobab, cashews, peppers, and onions register an increase in sensitivity, probably because the projected increase in temperatures may intensify heat and moisture stress. For instance, in Tambacounda, there is an increase in sensitivity for Mango, onion and baobab while in Sedhiou increase in sensitivity is exhibited in onion, madd, baobab and ditakh.

3.3 Exposure to natural hazards

Senegal remains vulnerable to climatic shocks including natural hazards that are predicted to increase in magnitude and extent because of climate variability (Simonet and Jobbins, 2016). These hazards include droughts and floods which recur seasonally, affecting livelihoods. Increasing precipitation and rising sea levels pose a great risk to people living in coastal, urban areas, who account for approximately 67% of Senegal's population (Croitoru et al., 2019; USAID, 2011). Variation in the start of the growing season, meanwhile, increases the vulnerability of farmers who lack access to irrigation because they are unable to schedule the timing of cropping activities such as planting and harvesting. In assessing vulnerability, we mapped natural hazards as shown in Table 1 below.

Droughts experienced in the 1970s and 1980s contributed to food insecurity in Senegal and the Sahel in general (USAID, 2017). Recent drought events in 2000 led to a 74% decline in groundnut revenues and diminished revenues for millet and sorghum by 60% (World Bank, 2011). More droughts occurred in 2002, affecting 284,000 people; in 2006/2007; and 2011, affecting 806,000 people (WFP, 2013). Droughts in 2014, 2017, and in 2018 impacted 245,000 people (Bhaga et al., 2020).

Floods, on the other hand, have become frequent due to increasing heavy rainfall events (USAID, 2017). Between 2000 and 2012, damages resulting from floods occurred in at least 8 years. In 2002, 179,000 people were affected; in 2008, 250,000 people; and in 2009, 360,000 people (WFP, 2013). The 2012 floods along the Senegal River and in low-lying areas of Greater Dakar affected over 265,000 people, exacerbating the drought-induced food security crisis of 2011/2012 (WFP, 2012). More recently, 2020 received higher-than-normal rainfall that led to flooding (ReliefWeb, 2020). In the absence of mitigation practices, consecutive floods and droughts can cause severe land degradation, worsening the crisis of food insecurity. Land degradation in Senegal is linked to the salinization of agricultural land, especially of rice paddies; to water erosion that causes stripping and gullying; and to wind erosion that removes the surface layer of soils and destroys their potential for production (Sow et al., 2016).

Table 1: Key natural hazards in Senegal

Hazard	Reference(s) that justify inclusion	Data link
Drought	(Epule et al., 2014) (Sall et al., 2015) (USAID, 2017)	https://bit.ly/2pgeN0p
Soil erosion	(Sow et al., 2016)	https://bit.ly/2JBU0eC
Flooding	(USAID, 2017) (WFP, 2013)	https://bit.ly/34kl9ux
Fires	(Mbow et al., 2000) (Frederiksen et al., 1990) (Nielsen et al., 2003)	https://go.nasa.gov/3200nPc
Salinization	(Sow et al., 2016) (Thiam et al., 2019) (Diack et al., 2019) (Wopereis et al., 1998)followed by single-cropped drained fields (1.6 dS m-1	http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/soil-qualities-data/en/
Waterlogging	(Komivi et al., 2018) (Diack et al., 2017)	http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/soil-qualities-data/en/

We extracted the data in raster format as an average for each arrondissement of Senegal and then normalized to a scale from 0 to 1. For each arrondissement, this data was later used to calculate vulnerability by applying equation 1. Figure 4 shows the spatial distribution of the six natural hazards considered: aridity, erosion, fire, flood, salinization, and waterlogging. Aridity affects the northern areas of Senegal, fire the southeastern areas, and erosion the central areas; flooding and salinization are particularly impactful in the southwestern areas of Ziguinchor and Sedhiou and in areas close to the coast. Waterlogging is mostly experienced in the southern areas of Senegal, such as the Casamance, which also receives high levels of rainfall. Exposure to arid conditions is particularly acute in the north and less so in the south.

We calculated changes in temperature for the four scenarios to show the rate at which

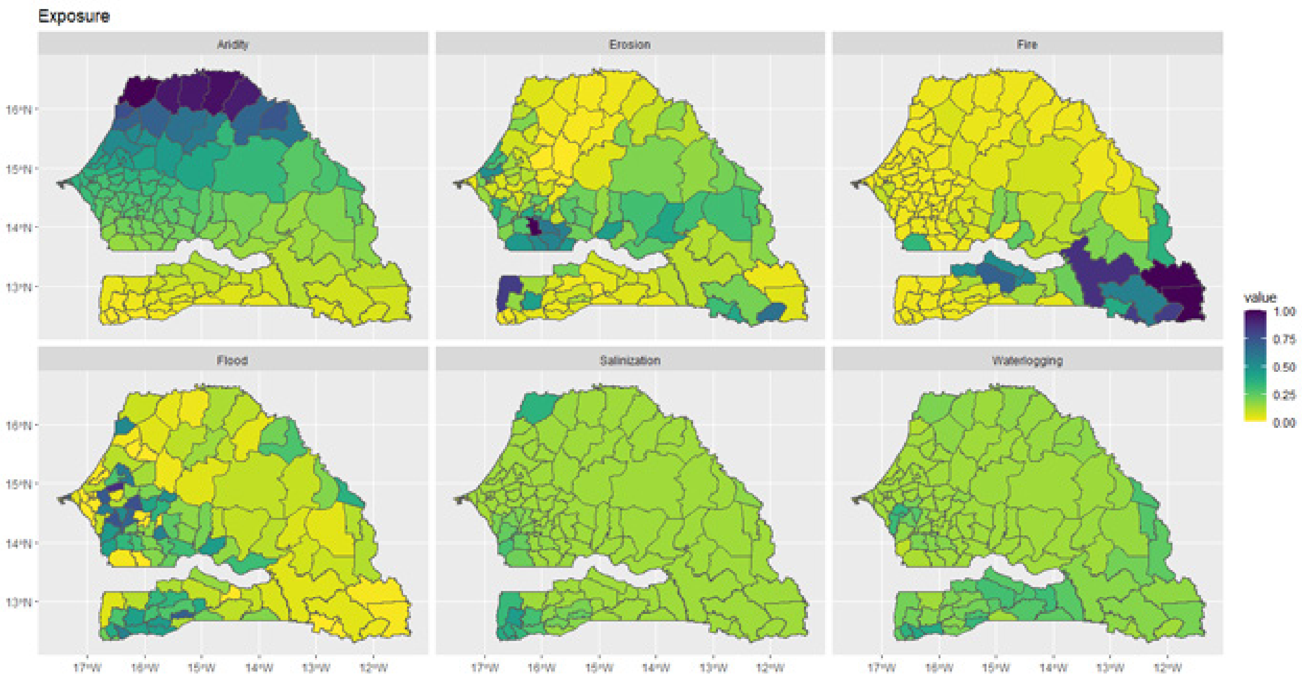

Figure 4: Spatial distribution of natural hazards across Senegal

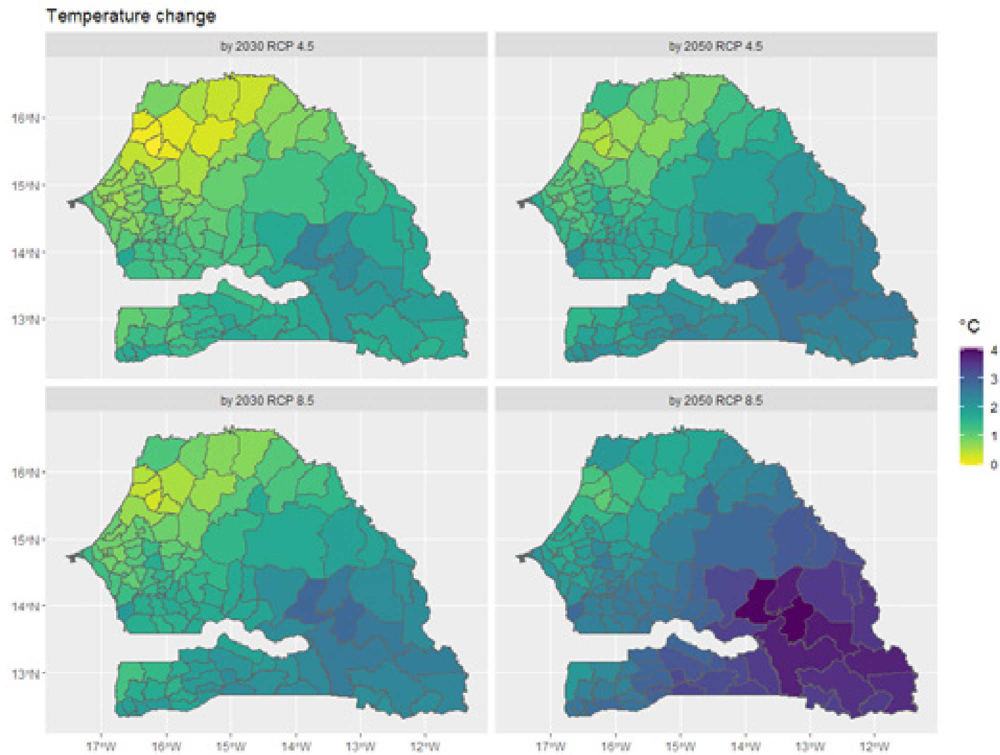

Figure 5: Temperature changes under RCPs 4.5 and 8.5 for the 2030s and 2050s

temperatures in Senegal are projected to increase (Figure 5). By the 2030s for RCP 4.5, temperatures are projected to increase slightly in eastern and southeastern Senegal, with the highest increase in Tambacounda Region. In some parts of Thies and Louga Regions, temperatures will remain similar to the present. By the 2030s for RCP 8.5. and by the 2050s for RCP 4.5, temperatures will be slightly higher compared to RCP 4.5 by the 2030s. Even greater temperature changes are projected under RCP 8.5 for the 2050s, particularly for the east, south, and southeastern areas of Senegal. Some arrondissements in Tambacounda Region will experience the greatest increases in temperature. Changes in temperature signify heat stress, which negatively impacts agriculture.

3.4 Adaptive capacity

Adaptive capacity refers to the ability of a system to prepare for climate stresses and changes in advance (Smit et al., 2003) or the ability to adjust and respond to the effects caused by climate change (IPCC, 2014). Increased adaptive capacity means better opportunities for systems to manage climate impacts of varying magnitudes (IPCC, 2012). For this vulnerability analysis, we gathered geospatial data on the variables that enhance adaptive capacity in Senegal (Table 2). We then normalized these variables so that 0 indicates lack of adaptive capacity and 1 corresponds to absolute adaptive capacity. For example, poverty was reciprocated so that a higher value shows low adaptive capacity.

Table 2: Adaptive capacity variables used in the vulnerability assessment for Senegal

Variable	Description
Crop diversification	Obtained by counting the total number of crops that are growing in each arrondissement. Crop distribution areas were taken from MapSPAM, the website of the Spatial Production Allocation Model (You et al., 2017).
Literacy rate	The percentage of the population in a given age group that can read and write. The adult literacy rate was obtained from the proportion of adults who had accessed primary education.
Dependency ratio	The ratio of, on one hand, the number of children aged 0-14 years and older persons aged 65 years or above, to on the other hand the working-age population between 15 and 64 years old (UN, 2006).
Access to health care	Distance to health care facilities (Maina et al., 2019)
Institutional capacity	The institutional capital index relates to the “governance index”, “conflictuality index”, and “environmental management index” of an institution (ClimAfrica, 2014).
Access to markets	Travel time to major cities is used as a measure of the accessibility of markets.
Poverty index	The proportion of the population living in households below the international poverty line, where the average daily consumption or income per person is less than $1.25 a day measured at 2005 international prices adjusted for purchasing power parity.
Stunting	The percentage of children under 5 years old whose standard score (z-score) falls below -2 standard deviations from the median height-for-age according to the World Health Organization (WHO) Child Growth Standards.
Wasting	The percentage of children under 5 years old whose standard score (z-score) falls below -2 standard deviations from the median weight-for-height according to the WHO Child Growth Standards.
Underweight children	The percentage of children under 5 years old whose standard score (z-score) falls above +2 standard deviations from the median weight-for-age according to the WHO Child Growth Standards.
Technological capacity	A combination of two underlying indexes: the “household technology index” and the “infrastructure index”. Technological capacity is linked with the diffusion of basic life technology and infrastructure, such as transportation networks.

Variable	Description
Access to water	Distance to the nearest water body. This variable represents access to irrigation and water for household consumption.
Under-5 mortality	Refers to the probability of dying between birth and exactly five years of age, expressed per 1,000 live births.
HIV prevalence	Percentage of the population living with HIV per 1000 people.
Food insecurity	People experiencing insufficient food consumption. This variable is expressed as poor or borderline food consumption, according to the Food Consumption Score.
Irrigable areas	Areas considered to have high potential for irrigation. The closer they are to water sources, the more suitable these areas are, and areas with soils containing more clay are also more suitable for irrigation because clay improves soil's water holding capacity.
Malaria mortality	Under-5 mortality from malaria infections.
Access to electricity	Access to electrical energy (Falchetta et al., 2019).
Residual water irrigation potential	Areas where water is predicted to remain on the soil longer after rainfall. This variable is estimated using data such as slope and soil's water-holding capacity, clay, and organic carbon content.
Soil fertility	Soil fertility index (Lu et al., 2002).
Phone access	Number of households owning a mobile phone.

The indicators of adaptive capacity represented here varied greatly across Senegal's various regions and arrondissements. For instance, some arrondissements had very low adaptive capacity associated with poverty, but high adaptive capacity associated with crop diversification and access to hospitals, markets, and irrigable areas. Rates of stunting, underweight children, wasting, malaria, and poverty are generally high in the western parts of the country. In addition, access to health care, water, markets, and soil fertility are low in western areas. These variables improve in the east and toward Dakar. Regions around Dakar and Ziguinchor have lower rates of stunting, underweight children, and wasting, and better access to health care, water, and markets; these regions are also characterized by low poverty rates and higher levels of soil fertility. In comparison to western Senegal, eastern regions face high rates of HIV prevalence and low access to electricity (Figures 6a and 6b).

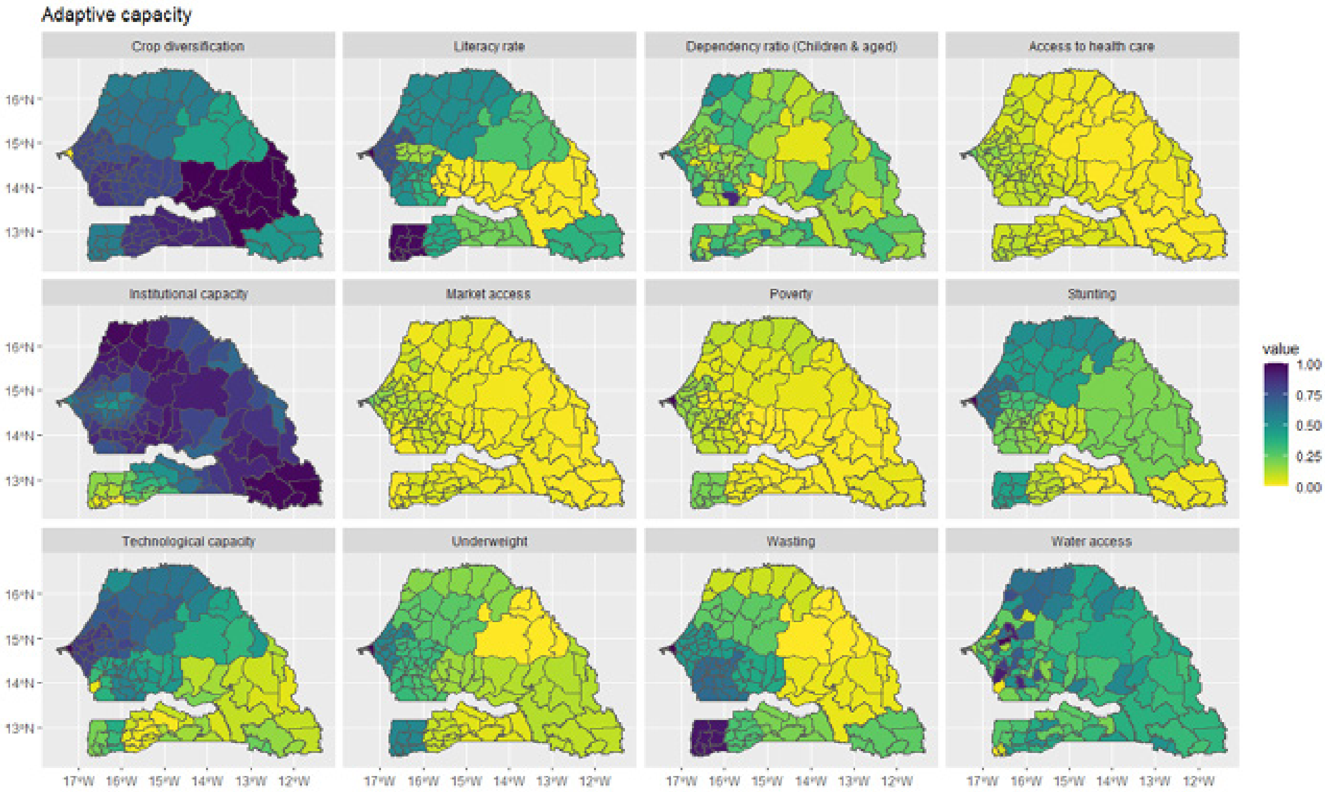

Figure 6a: Spatial distribution of adaptive capacity indicators for Senegal. A value of zero indicates no adaptive capacity, and a value of 1 indicates absolute adaptive capacity.

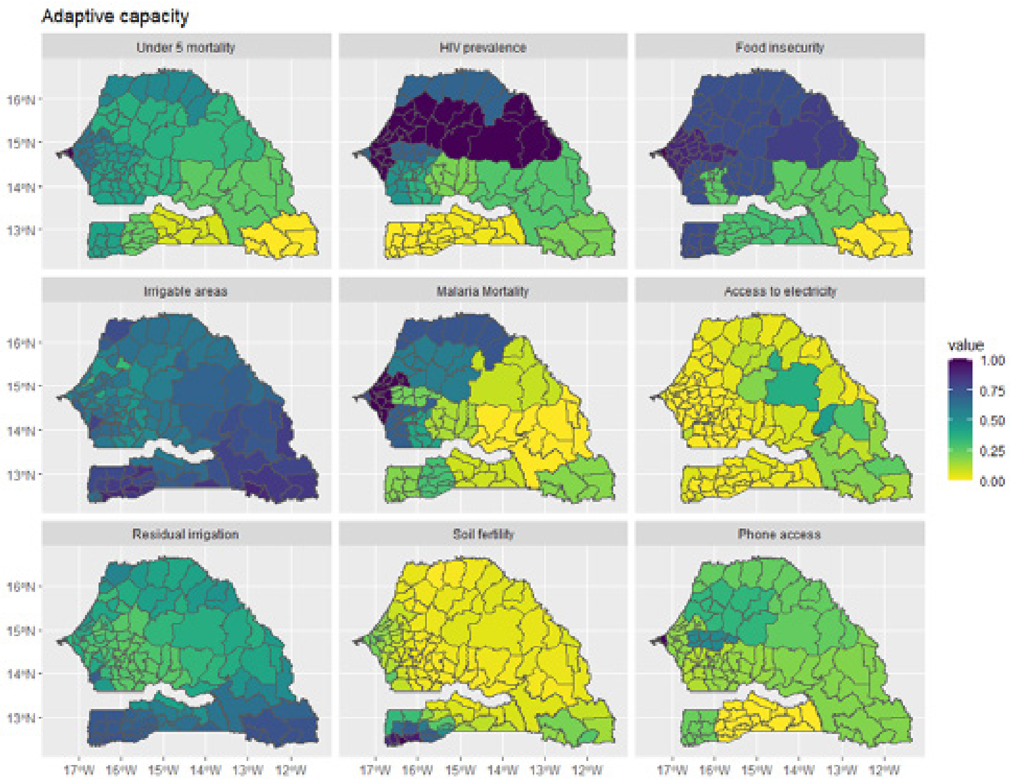

Figure 6b: Spatial distribution of adaptive capacity indicators for Senegal. A value of zero indicates no adaptive capacity, and a value of 1 indicates absolute adaptive capacity.

Variables that could help increase adaptive capacity include raising literacy rates by establishing more educational institutions and building their capacity; augmenting access to health care; bettering nutrition outcomes by reducing the rates of stunted, wasted, and underweight children; improving marketing and transportation; and diversifying crops and developing irrigation infrastructure, particularly in regions with irrigable areas.

3.5 The vulnerability of the Senegalese agricultural sector to climate change

By applying equation 1 using all the indicators for sensitivity, exposure, and adaptive capacity, we computed the vulnerability of the Senegalese agricultural sector to climate change. Our analysis focused on the future climate for RCP 4.5, an intermediate scenario that assumes partial implementation of the Paris Agreement, and RCP 8.5, the business-as-usual scenario, for the 2030s and 2050s.

Overall crop vulnerability in the 2030s under RCP 4.5 is greatest in the regions of Kaffrine, Tambacounda, Sedhiou, Kolda, and Kedougou, which are mainly in the central, southern, and southeastern parts of Senegal. There are also other specific arrondissements with high vulnerability elsewhere across the country (Figure 7a). On the other hand, vulnerability is lowest in areas near Ziguinchor and Dakar. Some areas in the north, especially in the regions of Thies and Louga, have lower vulnerability to climate change, probably because of their closeness to the capital, easy access to markets, low food insecurity, and high technological and institutional capacity.

For RCP 4.5 in the 2050s, vulnerability to climate change decreases, probably because of positive impacts from the implementation of regenerative measures to mitigate climate change effects (Figure 7b). On the other hand, under RCP 8.5 in the 2030s, vulnerability increases as compared to RCP 4.5 (Figure 7c). Under RCP 8.5 for the 2050s, climate change will exacerbate vulnerability in Senegal, especially in the north (Figure 7d).

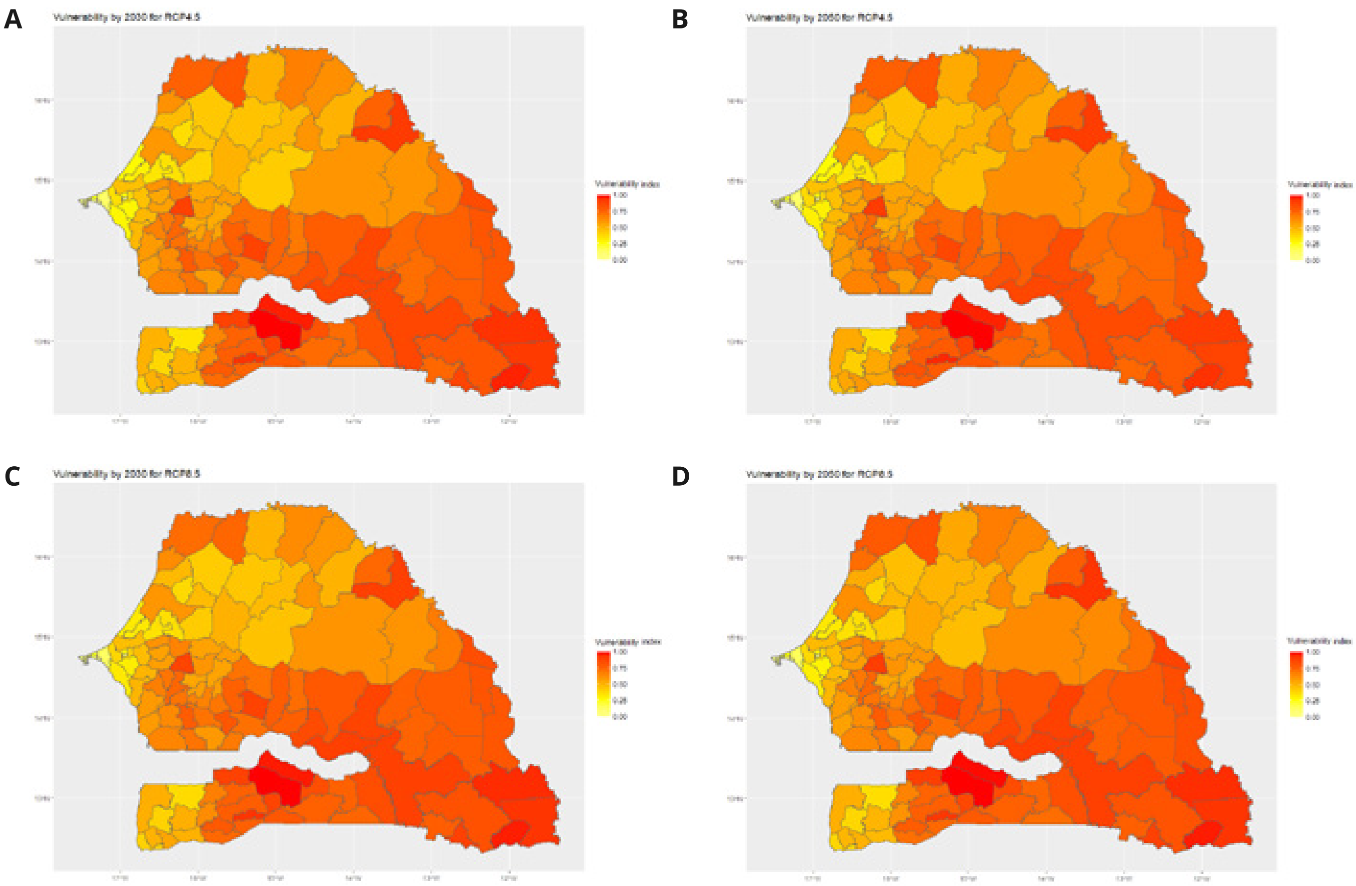

Figure 7: Overall vulnerability of Senegalese agriculture to climate change

In the areas of greatest vulnerability, that is, the central, southern, and southeastern parts of Senegal, most of the crops under analysis faced a significant reduction in suitability. These areas also experience heightened poverty rates, limited access to health facilities, high rates of stunted, wasted, and underweight children, and elevated malaria mortality. In additions, these areas have limited access to markets, depressed literacy rates, significant food insecurity, and low technological capacity. However, these areas also promise the greatest opportunity for farming using irrigation and carryover residual soil moisture.

All nine crops under analysis are most vulnerable towards southeastern Senegal, in the regions of Tambacounda, Kaffrine, Sedhiou, Kolda, and Kedougou. In the north, baobab trees, ditakh and madd are highly vulnerable, and in the northeast, cashews, okra, mangoes, onions, peppers, and rice face high vulnerability. Madd, mangoes, baobab, and onions are highly vulnerable in areas where they are currently considered most suitable (Figure 8). This situation is attributed to heightened climatic variations in the east and south of Senegal that leads to overall declines in crop suitability. Under climate change, there will be a decline in crop suitability for rice in Tambacounda, Sedhiou, and Kedougou; for peppers in Tambacounda and Kolda; for ditakh in Sedhiou and Kolda; and for okra in Tambacounda.

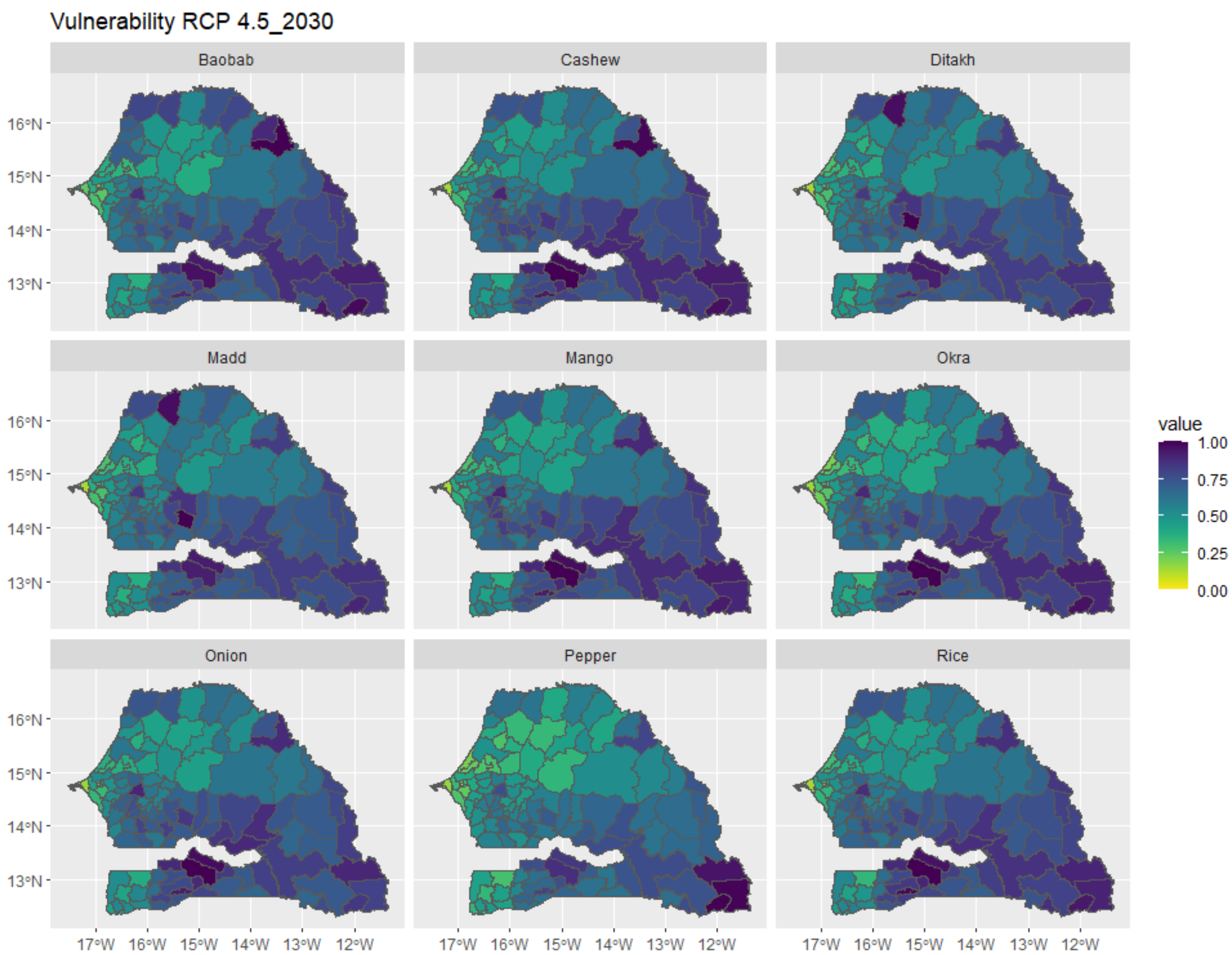

Figure 8: Contribution of different agricultural value chains to overall climate change vulnerability by the 2030s for RCP 4.5. Supplementary Figures S8–S10 in the Annex show results for RCP 4.5 by the 2050s and for RCP 8.5 by the 2030s and 2050s.

Conclusion

More than 70% of Senegal's population depend on agriculture, especially in the rural areas. With increasing youth populations, it is essential to empower young people with technical skills for profitable entrepreneurship and employment opportunities in agricultural value chains. The lack of economic opportunities is a key driver for migration in Senegal. Despite having about 1.5 million hectares of cultivated land and the potential to irrigate up to 240,000 hectares, at present the country irrigates only 10 percent of the cultivated area.

The vulnerability assessment for the selected crops in Senegal is based on their sensitivity to change, their exposure, and their adaptive capacities. We identified drought, soil erosion, flooding, fires, salinization and waterlogging as the main natural hazards representing exposure to climate change in Senegal. The adaptive capacity of the farming population can be enhanced by boosting literacy rates; increasing access to educational institutions and health facilities; improving nutrition outcomes to reduce the rates of stunted, wasted, and underweight children; and developing marketing, transportation, and irrigation infrastructure. Priority areas for ameliorating crop vulnerability include the eastern, southern, and southeastern areas of Senegal, which encompass Kaffrine, Tambacounda, Sedhiou, Kolda, and Kedougou Regions.

Crop suitability was modelled for nine crops: baobab, cashew, ditakh, madd, mango, onion, okra, pepper, and rice, which were identified as the most promising crops for socio-economic progress in the regions of Tambacounda and Sedhiou. Under climate change, there will be a decline in crop suitability for rice in Tambacounda, Sedhiou, and Kedougou; for peppers in Tambacounda and Kolda; for ditakh in Sedhiou and Kolda; and for okra in Tambacounda.

All nine crops under analysis are most vulnerable towards the south and the southeastern Senegal, including our project regions of Tambacounda and Sedhiou. This situation is attributed to heightened climatic variations in the east and south of Senegal that leads to overall declines in crop suitability. Under climate change, there will be a decline in crop suitability for rice in Tambacounda, Sedhiou, and Kedougou; for peppers in Tambacounda and Kolda; for ditakh in Sedhiou and Kolda; and for okra in Tambacounda. Various climate smart interventions will therefore be of most importance to reduce the effects of climate change on the selected value chains. The high rate of land degradation needs to be checked with adoption of practices such as reforestation as well as technologies that increase crop cover and reduces erosion. This will assist in storing moisture in the soil for a longer duration enhancing crop growth. Fertility depletion associated with monocropping is common in Senegal and needs to be replaced by technologies such as intercropping or crop rotation. Irrigation as a substitute for the high dependence on rainfall in crop growing as well as the use of flood waters for irrigation through water harvesting and flood recession farming should be taken into consideration.

Climate change is increasing agricultural risks with delayed onset, increased dry spells, and increasing droughts. Increasing temperatures contribute to high evapotranspiration rates with negative effects on yields. The AVENIR project will promote Climate-Smart Agriculture (CSA) and irrigation technologies, which present an opportunity for addressing the challenges to improve agricultural production systems adaptation especially under the new realities of climate change.

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Annex: Supplementary figures

1. Crop suitability

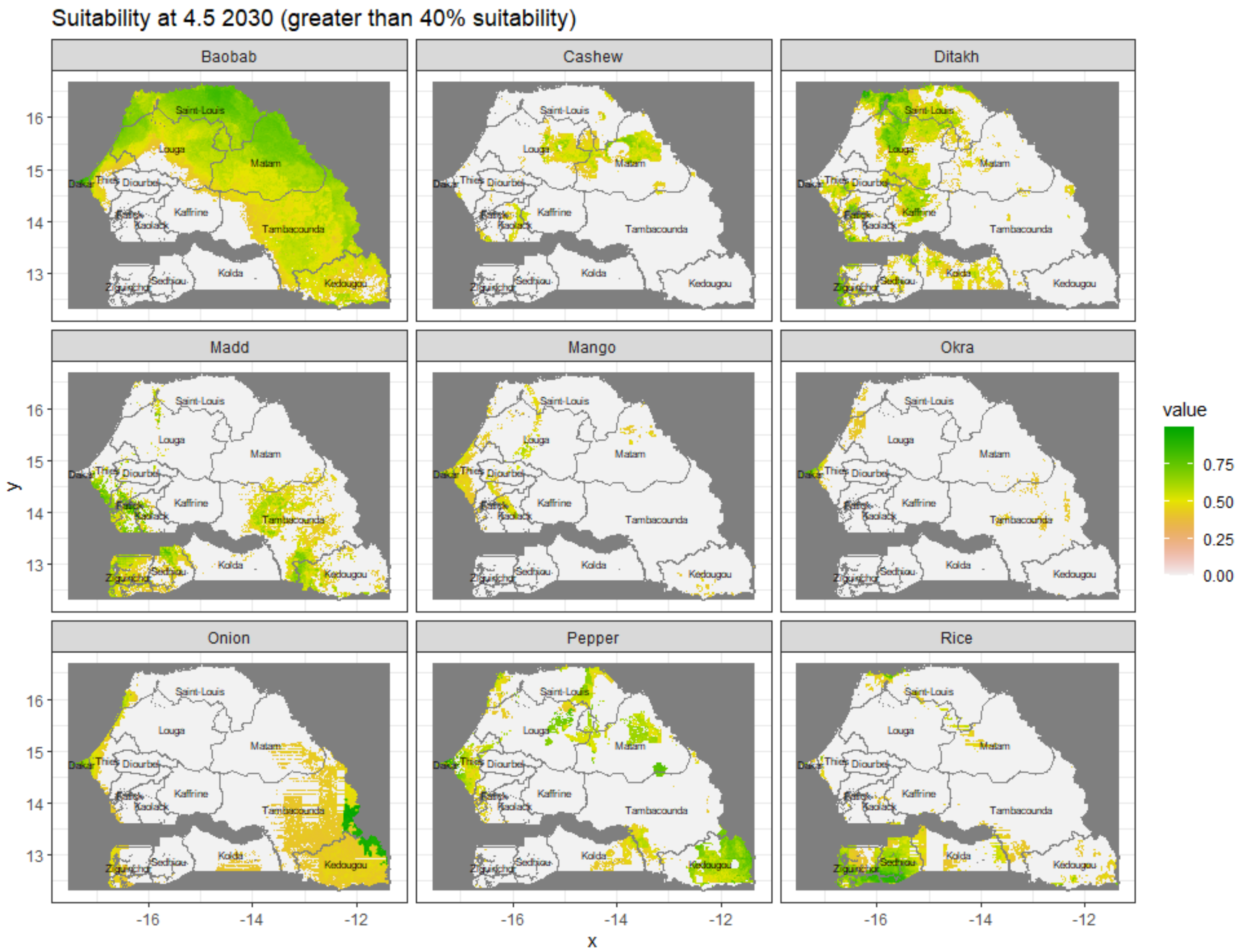

Figure S1. Crop suitability of the nine value chains by the 2030s for RCP 4.5

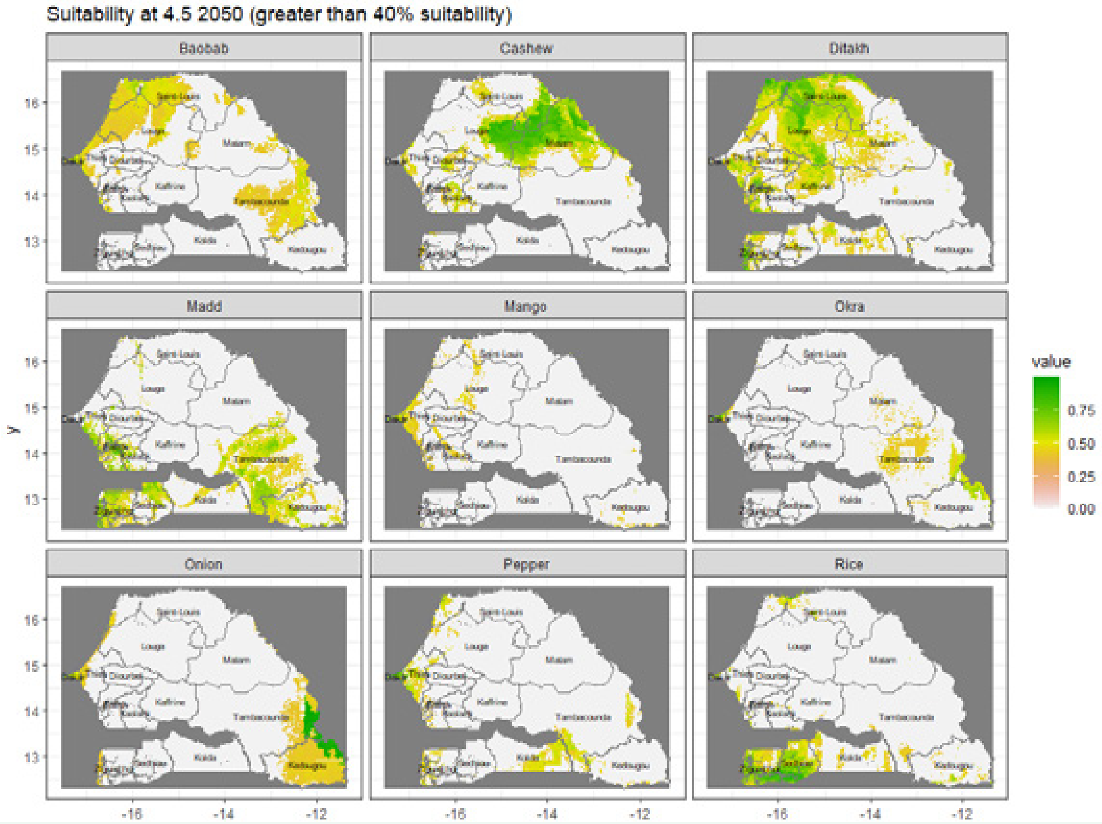

Figure S2. Crop suitability of the nine value chains by the 2050s for RCP 4.5

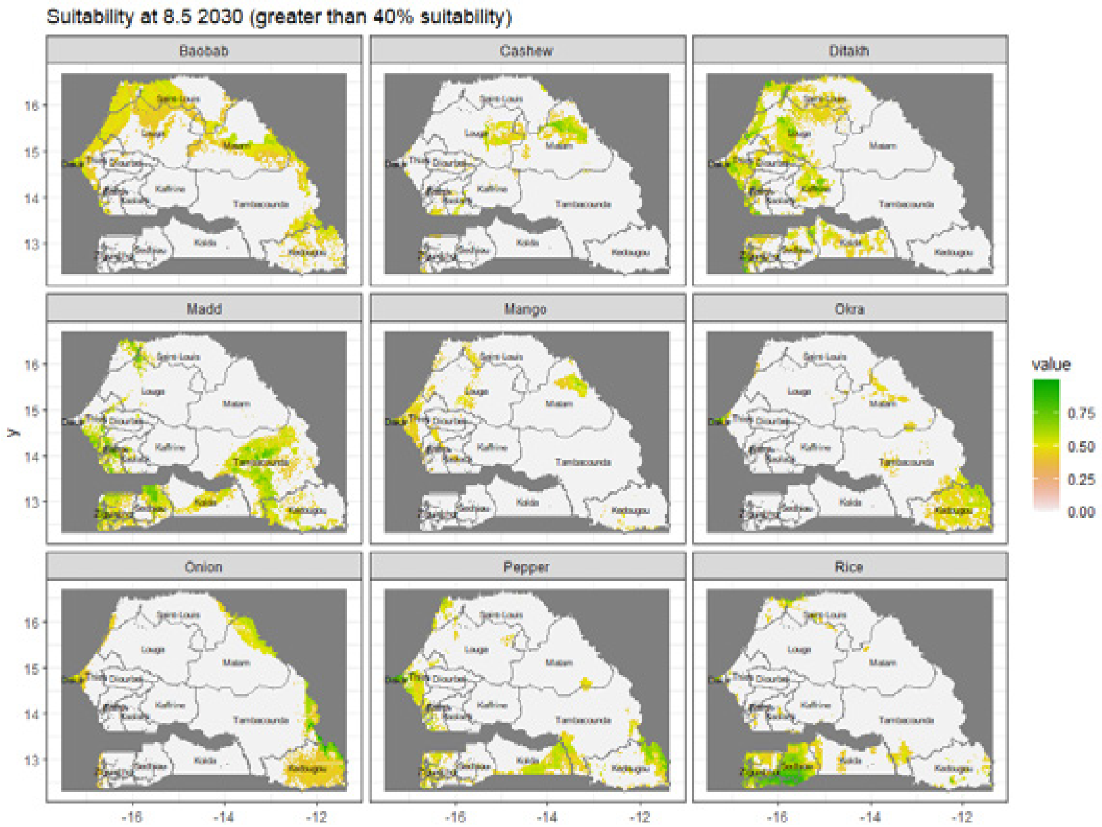

Figure S3. Crop suitability of the nine value chains by the 2030s for RCP 8.5

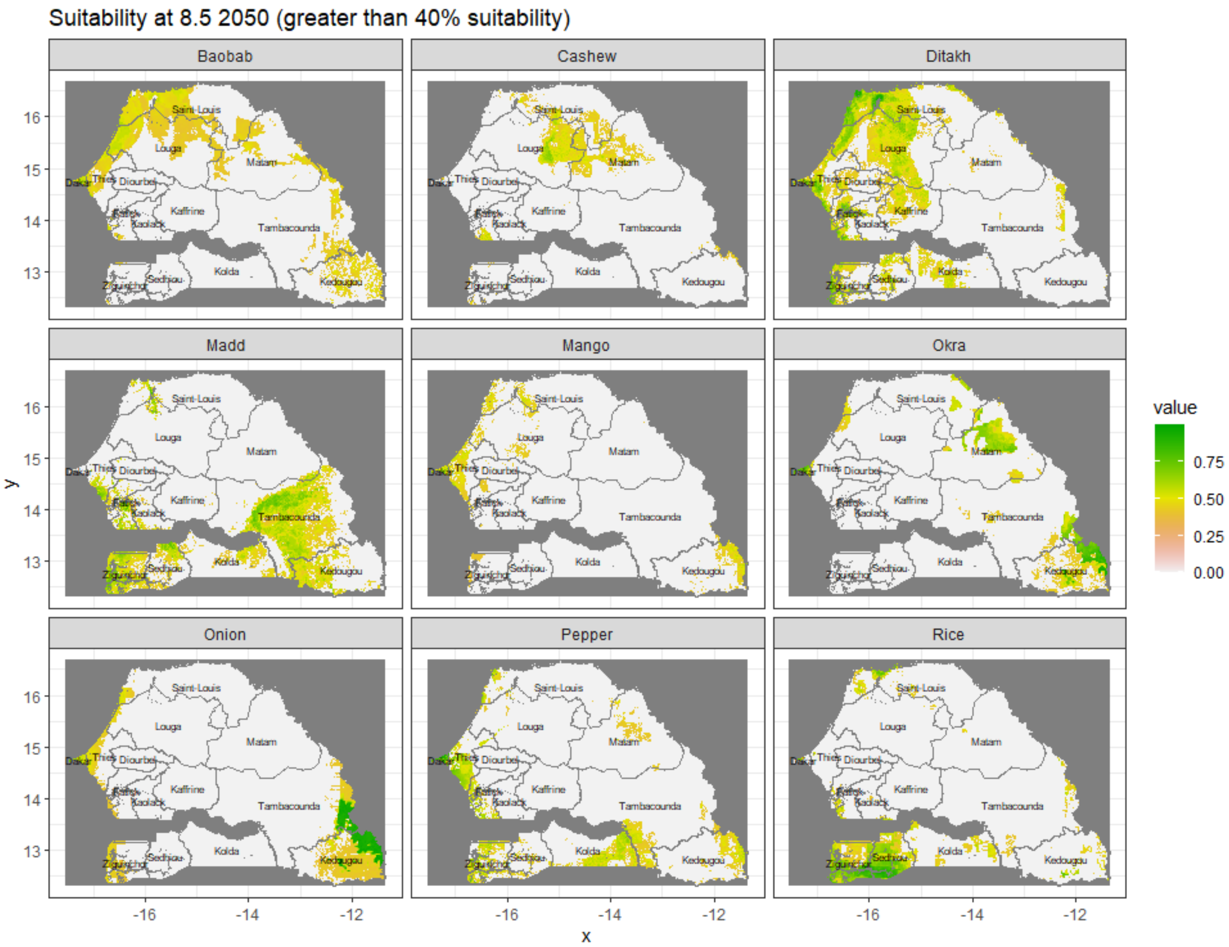

Figure S4. Crop suitability of the nine value chains by the 2050s for RCP 8.5

2. Sensitivity

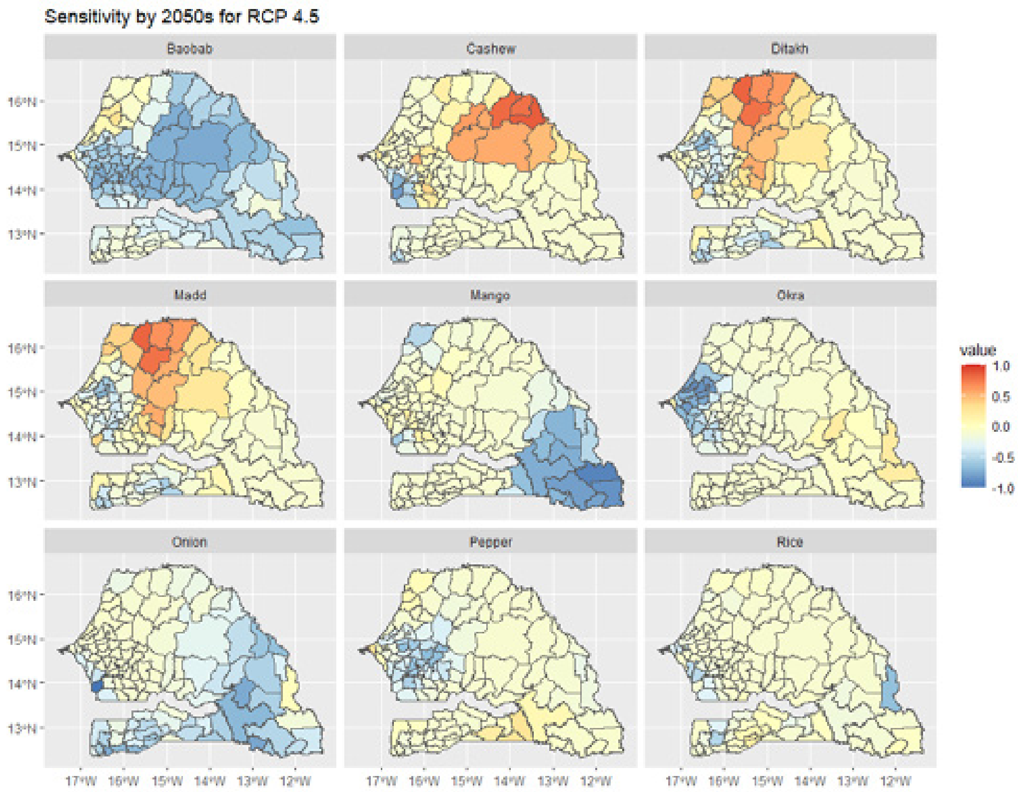

Figure S5. Sensitivity of the nine value chains to climate change by the 2050s for RCP 4.5

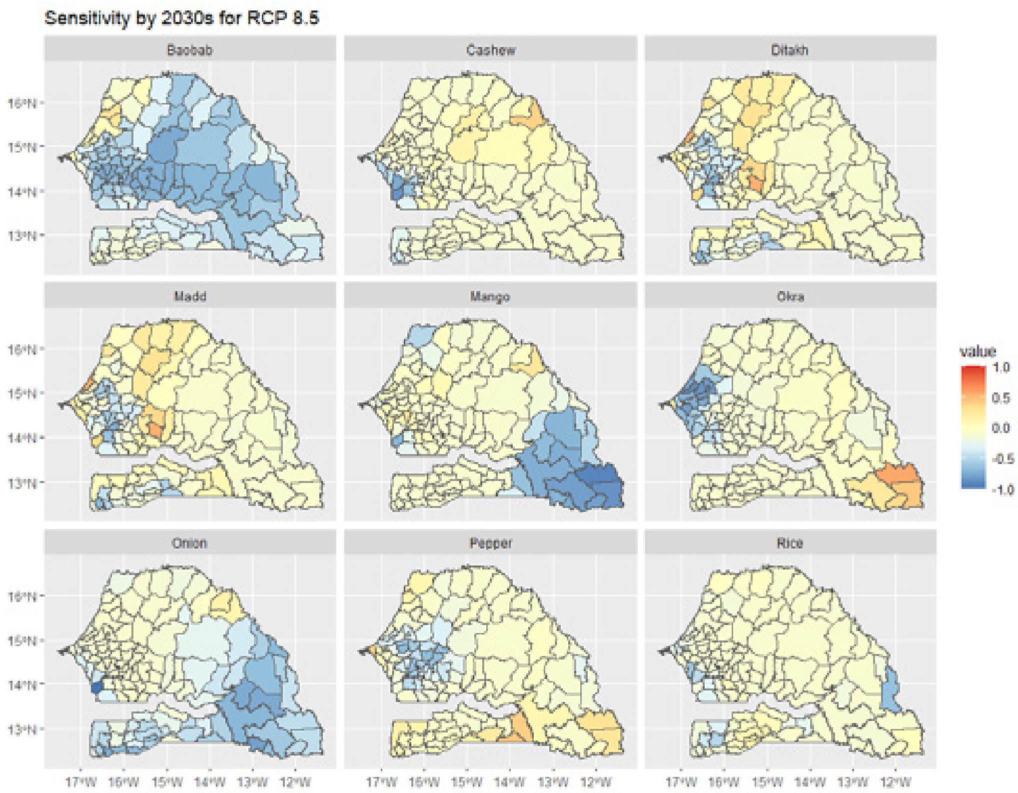

Figure S6. Sensitivity of the nine value chains to climate change by the 2030s for RCP 8.5

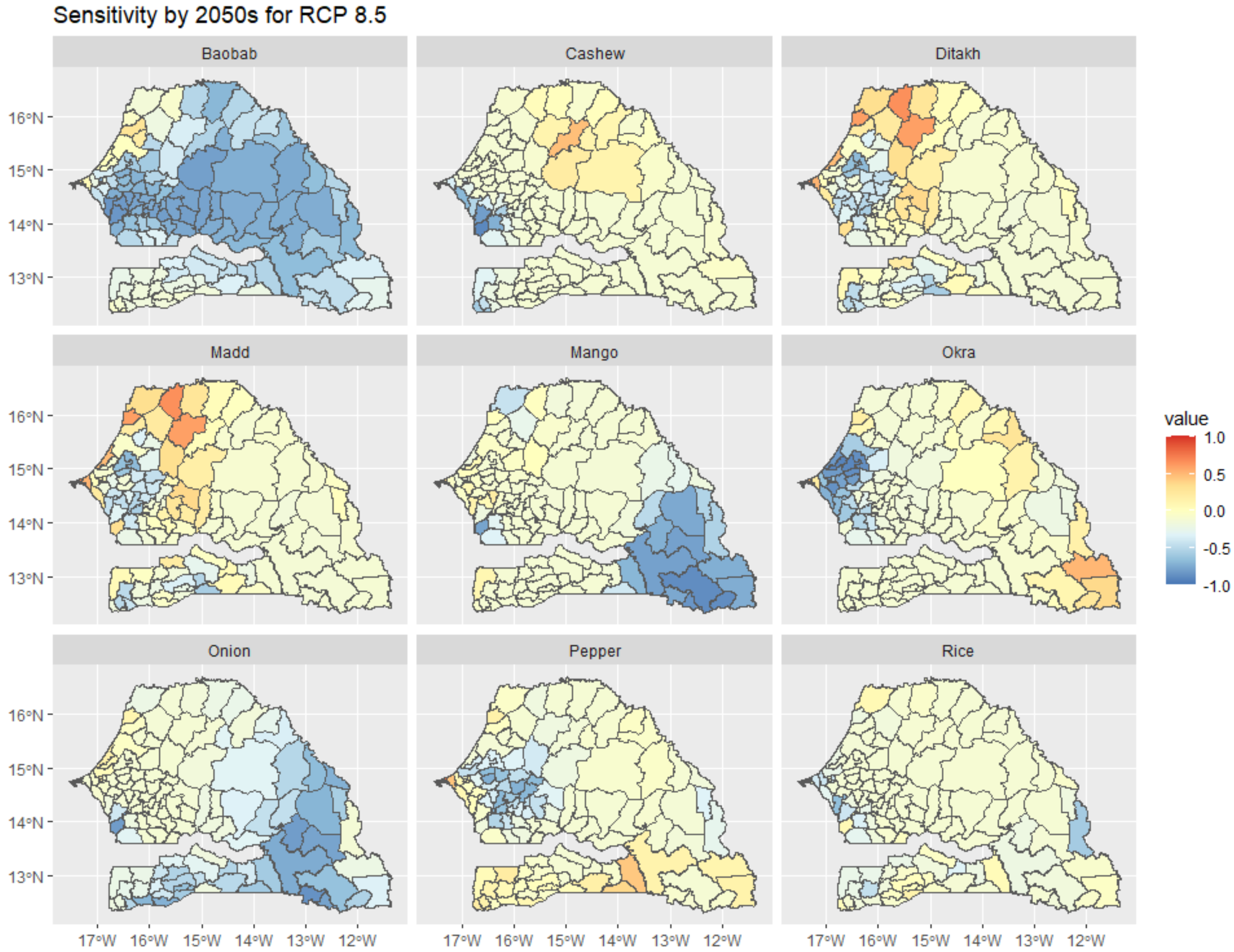

Figure S7. Sensitivity of the nine value chains to climate change by the 2050s for RCP 8.5

3. Vulnerability

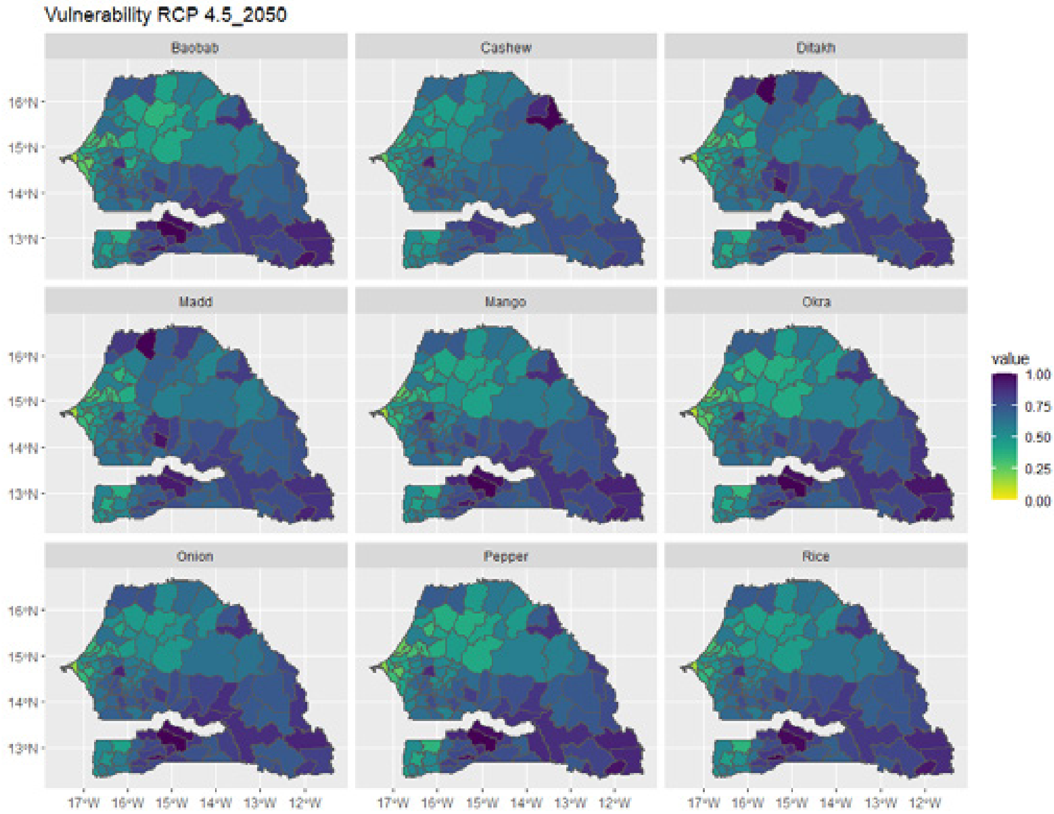

Figure S8: Contribution of the nine value chains to overall climate change vulnerability by 2050 for RCP 4.5

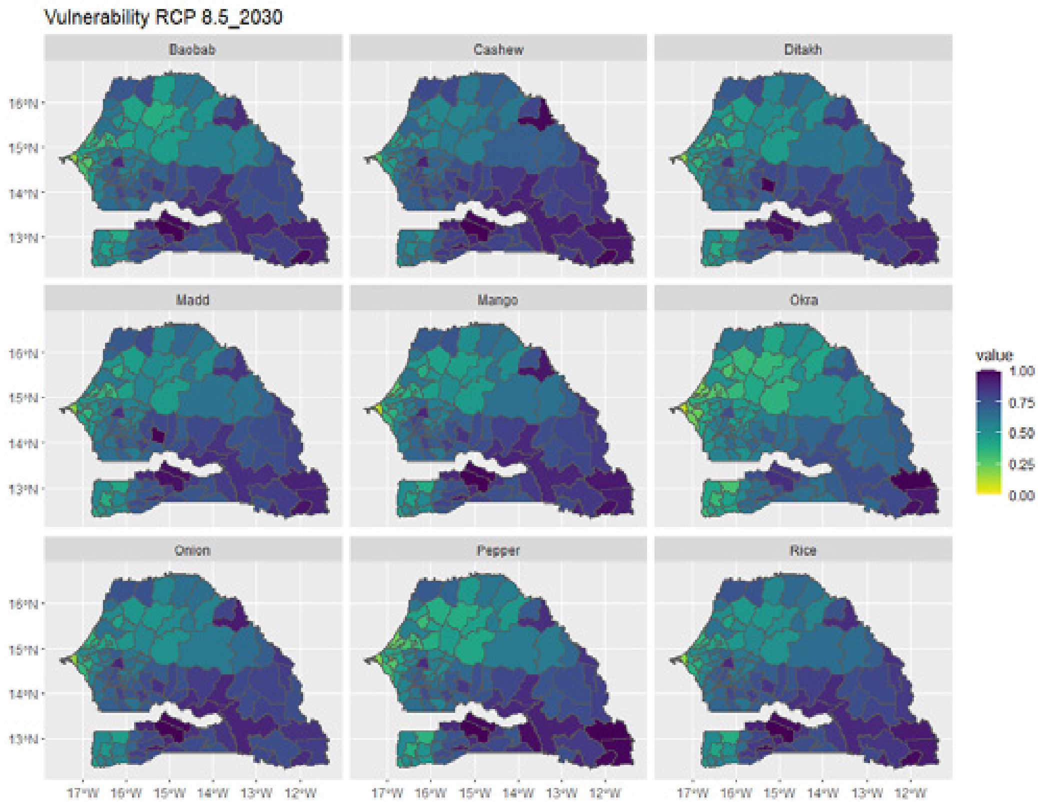

Figure S9: Contribution of the nine value chains to overall climate change vulnerability by 2030 for RCP 8.5

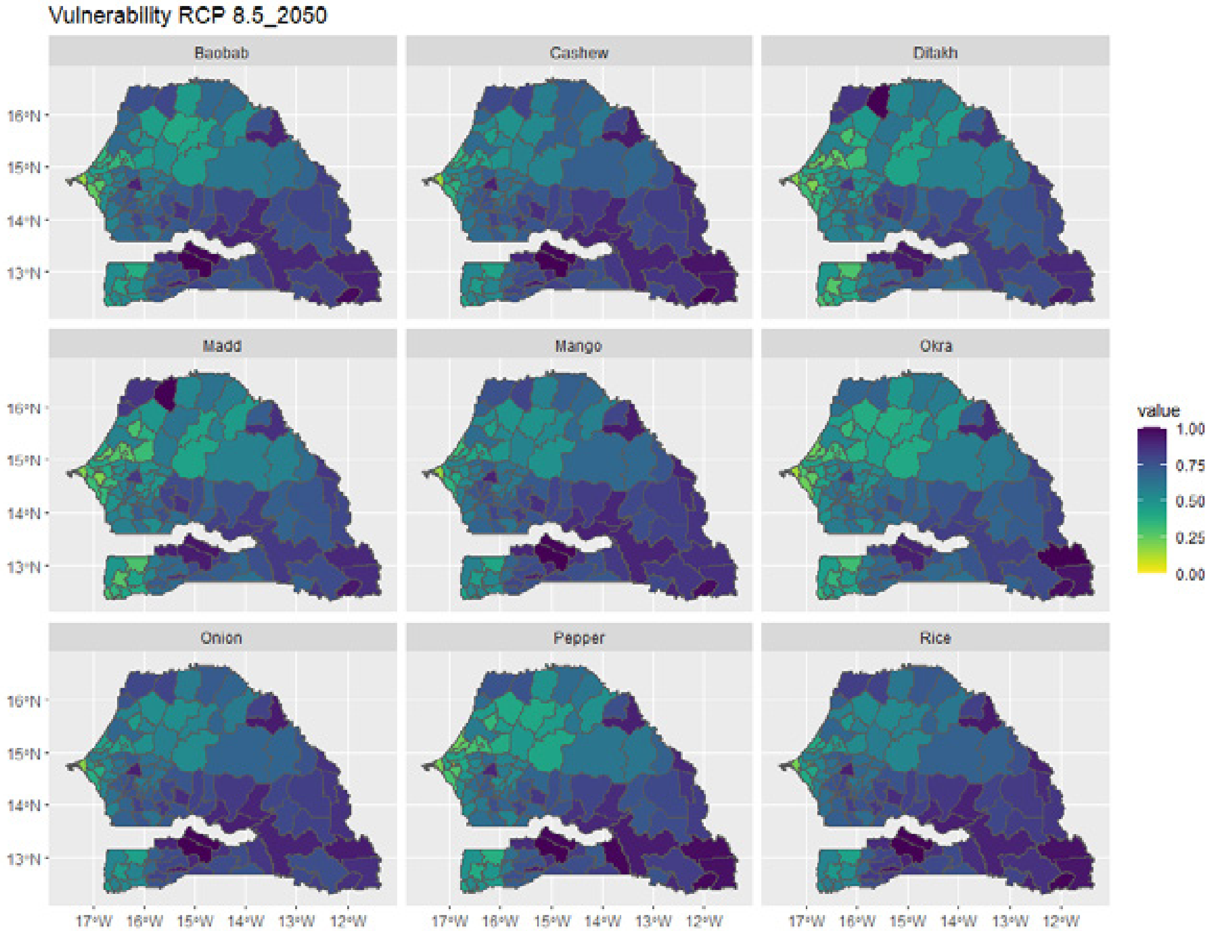

Figure S10: Contribution of the nine value chains to overall climate change vulnerability by 2050 for RCP 8.5

Alliance

Bioversity International and the International Center for Tropical Agriculture (CIAT) are part of CGIAR, a global research partnership for a food-secure future.

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