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Management interventions of pearl millet systems for attaining cereal self-sufficiency in Senegal

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Critical management interventions to target the yield potential for each environment are key to food security, increasing the resilience of current agricultural systems in Senegal. Cereal production is highly dependent on pearl millet (*Pennisetum glaucum* L.) rainfed systems as one of the major field crops for smallholders. This study aims to (i) quantify the production of pearl millet at the department level for the last quinquennial (until 2020), (ii) assess the impact of weather (temperature and precipitation) on the millet-based supply of cereal demand, and (iii) investigate, through crop modeling, the impact of millet-based supply of cereal demand by comparing recommended management interventions with smallholder-based strategies at the department level. Millet-based cereal supply–demand was estimated considering the observed population and the supply via the simulated pearl millet production (obtained using the APSIM-Millet model) at the department level from 1990 to 2021. High temperature and low precipitation occurrence presented a frequency of 35% across departments, leading to a reduction in millet production by roughly 6% relative to the normal average for 32 years. Adoption of recommended management showed the potential to increase the millet supply, more than doubling the current cereal supply, closing the current supply–demand gap (89 kg inhabitant^{-1}). Achieving future cereal self-sufficiency will also require an intensification of other cereal production.

KEYWORDS

adaptation practices, APSIM-Millet model, cereal supply, crop management, environment characterization, food security

1 Introduction

To address the imbalance in food production and population growth, Africa will need to produce at least 50% more food by 2050 to feed a projected 2.5 billion population (Godfray, 2010; McKenzie and Williams, 2015). In addition, climate variability poses a threat to countries with rainfed agriculture-based food production systems. In this context, frequent and severe droughts in sub-Saharan Africa have made climatic variability a priority for food policy and investments. The scarce and erratic pattern of precipitation, combined with environmental degradation, has led to hunger and malnutrition in this region (Wheeler and Von Braun, 2013; Rasmussen et al., 2016). The minimum requirements for cereal self-sufficiency in sub-Saharan African countries (250 kg inhabitant^{-1}; Fusillier, 1995) are rarely met by current cereal production. Not only is the current cereal demand not fully met but also, more complexly, projections have shown that the supply will drop below 50 kg inhabitant^{-1} by 2050 (Defrance et al., 2020). More specifically for Senegal, agriculture is the main source of income for rural households, and food production needs to increase by 60 to 110% to meet the future needs of a growing population (Tilman et al., 2011). However, the overall increase in food accessibility and production will be constrained by several factors related to both economic and environmental domains (Opole, 2019). Food policies in the region need to focus on stimulating the production of products, such as cereals, but also on improving accessibility and availability at the household level (Rukuni and Kellogg, 2002; Zhou and Staatz, 2016).

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is an important cereal grain in arid and semi-arid regions. It has good nutritional properties compared to more conventional staple grains (Kothari et al., 2005), due to its content of essential micronutrients (e.g., iron and zinc), and its lack of gluten; making it a candidate crop for contributing to food and nutritional security (Debieu et al., 2018; Gowda et al., 2022). Furthermore, this crop is adapted to areas with marginal soils, relatively tolerant to high temperatures and low precipitation (<350 mm year^{-1}), where other cereals fail to grow (Prasad et al., 2017; Ullah et al., 2017). For these reasons, pearl millet is recognized as a crucial food source for less resourceful farmers in the semi-arid tropics and a key crop for ensuring food security (Vadez et al., 2012). In Senegal, pearl millet is the most extensively grown grain and is a staple food crop for smallholder farmers, covering more than 64% of the land under cereal production [Direction de l'Analyse,de la Prévision et desStatistiques Agricoles (DAPSA), 2022]. Unlike sorghum (*Sorghum bicolor* L.) and maize (*Zea mays* L.), which are confined to more humid areas, millet can be found throughout the country across different soil types and agro-ecological zones (Diatta et al., 2020). It is usually grown under rainfed and extensive conditions with lower or no inputs, resulting in on-farm attainable yields ranging from 500 to 900 kg ha^{-1} [Direction de l'Analyse,de la Prévision et desStatistiques Agricoles (DAPSA), 2022]. To offset the decline of productivity in millet-based systems, it is necessary to develop viable and accessible alternatives for farmers (Trail et al., 2016). Furthermore, a recent study demonstrated, via the use of crop modeling, that the adoption of a better management strategy (e.g., planting date and nitrogen fertilization) can mitigate the impact of climate change (Araya et al., 2022).

The current scenario of low yields for major field crops has led to an increase in food import dependence for Senegal (Van den Broeck et al., 2018), highlighting the need for a change in the production systems to achieve food self-sufficiency. Attaining high yields on existing cropland, especially in low-yielding countries, will be of great importance to the demand for food needed to make the systems more efficient and sustainable [Intergovernmental Panel on Climate Change (IPCC), 2007; Tilman et al., 2011]. In this context, a previous study employing a crop modeling approach aimed to evaluate and propose management adaptations for rainfed pearl millet systems in Senegal (Vieira Junior et al., 2023). In this study, changes in planting date and nitrogen fertilization were identified as potentially relevant management technologies to increase pearl millet yields and improve cereal self-sufficiency. However, a country-wide assessment is still needed to better understand the overall magnitude of cereal food insecurity and promote a relevant future way forward.

Therefore, this study focuses on providing an assessment of pearl millet-based supply of cereal demand at department level (total 37) via the application of the APSIM-Millet model to evaluate the impact of climate and management practices on food security in Senegal. The specific objectives of this project were to (i) quantify the production of pearl millet at the department level for the last quinquennial (2016–2020), (ii) assess the impact of weather (via changes in temperature and precipitation) on the millet-based supply of cereal demand, and (iii) investigate via crop modeling the impact of the recommended versus current smallholder-based management field interventions at the department level on the millet-based supply of cereal demand.

2 Materials and methods

This study proposed a comprehensive assessment of the pearl millet-based supply of cereal demand in Senegal, encompassing three distinct analyses. First, pearl millet supply characterization was conducted at the department level, utilizing observed data on pearl millet production and population. These data were employed to estimate the actual (2016 to 2021) pearl millet supply trends. Second, the weather characterization was performed to assess the impact of weather on the pearl millet supply. The temperature and precipitation data, covering the period from 1990 to 2021, were categorized into low or high based on their occurrence during growing seasons at the department level. Then, the weather characterization was established through the combination of temperature (low and high) and precipitation (low and high), resulting in four different weather conditions. Finally, the estimation of pearl millet-based supply of cereal demand was derived by analyzing simulated data, which served to evaluate two management practices within pearl millet systems. Long-term simulations (1990 to 2021) were performed for two distinct management practices for pearl millet systems: (i) representative of common practices adopted among smallholders in Senegal (standard management) and (ii) optimized interventions to enhance pearl millet production (recommended management). The resulting simulated data were integrated with observed data on the production of primary cereals cultivated in Senegal, enabling the assessment of how these two management practices for pearl millet systems influenced cereal supply dynamics at the country level (Figure 1). Data description, application, and source are presented in Table 1.

2.1 Data source

The presentation of data collection aligns with its sequential application in the three analyses conducted in this study: (i) characterization of pearl millet supply, (ii) weather characterization, and (iii) estimation of pearl millet-based cereal supply at the national level (Figure 1). Observed data on pearl millet production and population from the 2016 to 2020 were retrieved from the Directorate

FIGURE 1
Flowchart of the data collection, long-term simulations, and data analysis of pearl millet supply and cereal demand in Senegal.

of Agricultural Statistical Analysis and Projections, Ministry of Agriculture and Rural Equipment (DAPSA/MAER),[1] encompassing all departments where pearl millet producers are located in Senegal.

Weather data (1990 to 2021) for both environmental characterization and long-term simulations were obtained from the National Aeronautics and Space Administration—Prediction Of World Energy Resources (NASA POWER; Sparks, 2018). This dataset is composed of daily data on solar radiation (MJ m^{-2} day^{-1}) and maximum and minimum air temperature (°C). The precipitation (mm) data were collected from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS; Funk et al., 2015). Moreover, the soil data employed in the simulations were retrieved from SoilGrids (SoilGrids250m version 2.0; Poggio et al., 2021). Subsequently, the data were transformed into a soil profile format, which was consistent with the standard of the model using the apsimx package (Fernando-Miguez, 2022) in R software (R Core Team, 2021). The dataset employed for the long-term simulations consisted of soil texture (clay, silt, and sand contents; %), depth (cm), bulk density (g cm^{-3}), drained

1 https://www.dapsa.gouv.sn/

TABLE 1 Description, application, and source of collected data employed in the long-term simulations, weather characterization, and pearl millet-based supply of the cereal demand in Senegal.

Data	Description	Period	Application	Source
Pearl millet production	Reported data on annual pearl millet production (kg) at the department level.	2016–2021	Estimation of pearl millet supply	DAPSA/MAER
Pearl millet harvested area	Reported data on annual harvested area (hectares) of pearl millet at the department level.	2016–2021	Estimation of pearl millet-based supply of cereal demand	DAPSA/MAER
Population	Reported data on annual number of inhabitants at the department level.	2016–2021	Estimation of pearl millet supply; Estimation of cereal supply	DAPSA/MAER
Cereal supply	Reported data on cereal supply (kg inhabitant^{-1} year^{-1}) at the national level composed of maize (*Zea mays* L.), millet (*Pennisetum glaucum* (L.) R. Br.), rice (*Oryza sativa*), and sorghum (*Sorghum bicolor* L.).	1990–2021	Estimation of cereal supply	DAPSA/MAER
Strategies management	Most common farming practices (standard management) and recommended interventions (recommended management) for the pearl millet smallholders in Senegal.	-	Estimation of pearl millet-based supply of cereal demand; Long-term simulations	Vieira Junior et al. (2023)
Calibration	Crop parameters of the APSIM-Millet model calibrated for two most cultivated landrace types (early- and late flowering) of pearl millet in Senegal.	-	Long-term simulations	Vieira Junior et al. (2023)
Weather data	Solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), and precipitation (mm).	1990–2021	Weather characterization; Long-term simulations	NASA POWER (Sparks, 2018); CHIRPS (Funk et al., 2015)
Soil data	Texture (clay, silt, and sand contents; %), depth (cm), bulk density (g cm^{-3}), drained lower limit (mm mm^{-1}), drained upper limit (mm mm^{-1}), saturated water content (mm mm^{-1}), and pH.	-	Long-term simulations	Soil Grids (Hengl et al., 2014)

lower limit (mm mm^{-1}), drained upper limit (mm mm^{-1}), saturated water content (mm mm^{-1}), and pH (Table 1).

Harvested area data for pearl millet at the departmental level from 1990 to 2021 were sourced from DAPSA/MAER (see Footnote 1) and utilized in the estimation of millet-based supply. Moreover, to evaluate the impact of simulated management practices on pearl millet systems concerning cereal supply in Senegal, observed data on cereal supply at the national level, composed of maize (*Zea mays* L.), rice (*Oryza sativa*), sorghum (*Sorghum bicolor* L.), and pearl millet (*Pennisetum glaucum* (L.) R. Br.), from 1990 to 2021, were retrieved from DAPSA/MAER (see Footnote 1).

2.2 Pearl millet supply characterization

The actual supply *per capita* of pearl millet was estimated for all 37 producing departments of pearl millet in Senegal from 2016 to 2020 (Supplementary Figure S1). Employing observed data on production and population, the pearl millet supply *per capita* was calculated for each year as described by Defrance et al. (2020), Eq. 1.

$$\text{Pearl millet supply} = \frac{\text{Production}}{\text{Population}} \quad (1)$$

In which the pearl millet supply (kg inhabitant^{-1} year^{-1}) is the production of pearl millet (kg) divided by the number of inhabitants for each year between 2016 and 2020.

2.3 Weather characterization

Weather characterization was conducted for all producing departments of pearl millet in Senegal. This analysis considered precipitation and mean temperature as the main key variables, following the methodology proposed by Balboa et al. (2019). Weather conditions, between 1990 and 2021, were classified considering the mean across years of cumulative precipitation during the growing season (high precipitation: HP and low precipitation LP) and the average during the growing season of the daily mean temperature (high temperature: HT and low temperature: LT). This process resulted in four weather groups: (i) high temperature and low

TABLE 2 Average, minimum, and maximum values of daily mean temperature during the growing season and cumulative precipitation during the growing season for the four weather groups (high temperature and low precipitation, HT-LP; high temperature and high precipitation, HT-HP; low temperature and high precipitation, LT-HP; and low temperature and low precipitation, LT-LP) in Senegal between 1990 and 2021.

Weather	Mean temperature			Precipitation		
	Average	Minimum	Maximum	Average	Minimum	Maximum
HT-HP	29.0	27.2	32.8	676	245	1751
HT-LP	29.4	27.4	33.1	508	97	1,355
LT-HP	28.4	26.7	31.3	721	248	2,174
LT-LP	28.4	26.8	31.3	541	124	1,353

TABLE 3 Description of the recommended management practices (planting date, plant density, and nitrogen fertilizer rate) simulated for the producing departments of Senegal.

Strategies	Planting date	Plant density (plants m^{-2})	N fertilizer rate (kg N ha^{-1})
1	After first rain greater than 20 mm (early)	6.6	100
2	20 days after first rain greater than 20 mm (medium)	6.6	100
3	40 days after first rain greater than 20 mm (late)	6.6	100
4	40 days after first rain greater than 20 mm (late)	3.3	40

precipitation (HT-LP), (ii) high temperature and high precipitation (HT-HP), (iii) low temperature and high precipitation (LT-HP), and (iv) and low temperature and low precipitation (LT-LP). This weather classification was performed independently for each producing department of pearl millet in Senegal (Supplementary Figure S2). At the national level, cumulative precipitation ranged from 97 to 2.174 mm, and the mean temperature ranged from 26.7 to 33.1°C between the four weather groups (Table 2).

2.4 Pearl millet management strategies

The standard management practices were defined as a baseline to benchmark with the recommended practices on pearl millet supply. The most common farming practices adopted by pearl millet smallholders in Senegal were retrieved from the most recent surveys and literature (last 10 years) by Vieira Junior et al. (2023). The planting date was set at the first precipitation greater than 20 mm and, after 30 May, considered as an early planting date. The plant density was defined as 1.1 plants m^{-2}. The N fertilization was defined as 30 kg N ha^{-1} of urea applied at two dates, 21 and 45 days after sowing.

The recommended management practices were previously established by Vieira Junior et al. (2023), aiming to achieve greater grain yield with reduced input use for each district of Senegal (Supplementary Figure S1). The recommended practices consisted of changes in the planting dates, plant density, and nitrogen (N) fertilizer rate (Table 3). The management practices were tested and proposed according to the weather and soil conditions of each district of Senegal. Then, these recommended management practices were grouped into four strategies according to their similarities (Table 3).

2.5 Long-term simulations

The simulations were performed using Agricultural Production Systems Simulator (APSIM) software platform version 7.10 (Holzworth et al., 2014). For this study, it was employed a previous calibration of the APSIM-Millet model (van Oosterom et al., 2001a,b, 2002) obtained from the study by Vieira Junior et al. (2023). This calibration aimed to represent the phenology and grain yield of two prominent pearl millet landraces (early-flowering and late-flowering) commonly cultivated in Senegal. The performance of the model in simulating pearl millet production at the department level was satisfactory based on statistical metrics (Supplementary Figure S3). Soil parameters and initial conditions were defined in accordance with the specifications described by Vieira Junior et al. (2023).

The simulations were conducted considering two management strategies outlined by Vieira Junior et al. (2023): (i) the current standard management based on the most common practices adopted by farmers in Senegal and (ii) the recommended management practices proposed for each district (Table 3). Grain yield was simulated for both management strategies for 32 years (from 1990 to 2021) across 351 locations distributed across the producing departments of pearl millet in Senegal, ranging the number of samples from 2 to 38 per department (average per department 9; Supplementary Figure S1) in Senegal. This comprehensive approach resulted in 22,464 distinct simulation scenarios, resulting from the combination of year, location, and management variables. The simulated locations were previously used to calibrate the model and represent the geospatial distribution of the two landraces adopted by farmers. The pearl millet production at the department level was obtained by multiplying the grain yield simulated (mean of all simulated points within each department) by the harvested area for each year (Supplementary Figure S4).

2.6 Estimation of pearl millet-based supply of cereal demand

In the last analysis of this study, the impact of management practices within pearl millet systems on meeting the cereal demand in Senegal was assessed, based on the methodology described by

Defrance et al. (2020). The reference benchmark for cereal self-sufficiency in sub-Saharan African countries, established by Fusillier (1995) at a minimum of 250 kg inhabitant^{-1} year^{-1}, was employed as a comparison. First, the simulated grain yield data were used to estimate the pearl millet supply (Supply$_{\text{simulated pearl millet}}$) for both standard and recommended management from 1990 to 2021, encompassing departmental and country levels (Eq. 2).

$$\text{Supply}_{simulated\ pearl\ millet} = \frac{Grain\ yield \times Haversted\ area}{Population} \quad (2)$$

where the Supply$_{\text{simulated pearl millet}}$ (kg inhabitant^{-1} year^{-1}) is the pearl millet-based cereal production (kg) *per capita* (population in number of inhabitants) for each year between 2016 and 2020.

Subsequently, observed data on cereal supply *per capita* (kg inhabitant^{-1} year^{-1}) from 1990 to 2021 were utilized to compute the historical cereal supply (Eq. 3). This consisted of summing the annual supply reported for maize, rice, sorghum, and pearl millet at the country level, hereafter referred to as cereal observed (Supplementary Figure S4).

$$\text{Cereal}_{observed} = Supply_{maize} + Supply_{rice} + Supply_{sorghum} + Supply_{pearlmillet} \quad (3)$$

Here, Supply$_{\text{maize}}$, Supply$_{\text{rice}}$, Supply$_{\text{sorghum}}$, and Supply$_{\text{pearl millet}}$ represent the annual supply reported for maize, rice, sorghum, and pearl millet (standard management), respectively. The summation of these individual supplies yields the total cereal supply (Cereal$_{\text{observed}}$) at the national level (kg inhabitant^{-1} year^{-1}).

To evaluate the impact of management practices, the observed values of pearl millet supply were replaced by the values obtained in the simulations for the recommended management (hereafter cereal with pearl millet recommended management; Eq. 4).

$$\text{Cereal}_{with\ pearl\ millet\ recommended\ management} = Supply_{maize} + Supply_{rice} + Supply_{sorghum} + Supply_{pearl\ millet\ recommended\ management} \quad (4)$$

The Cereal$_{\text{with pearl millet recommended management}}$ (in kg inhabitant^{-1} year^{-1}) represents the cumulative supply, including both observed and simulated values. It is computed as the sum of the observed supplies for maize (Supply$_{\text{maize}}$), rice (Supply$_{\text{rice}}$), and sorghum (Supply$_{\text{sorghum}}$), along with the simulated supply under recommended management for pearl millet (Supply$_{\text{pearl millet recommended management}}$).

3 Results

3.1 Current pearl millet supply characterization (2016 to 2020): observed data analysis

The average production of pearl millet in Senegal between 2016 and 2020 was 868,319 tons, resulting in pearl millet supply *per capita* of 98 kg inhabitant^{-1} year^{-1}. The main producing region was located in the center of the country (Figure 2B), where four departments (Nioro Du Rip, Fatick, Foundiougne, and Malem Hodar; Supplementary Figure S1) represented 33% of the total country production (Figure 2B) and 30% of pearl millet supply (Figure 2C). Only one department, Malem Hodar, exceeded the minimum cereal requirement determined by FAO (250 kg inhabitant^{-1} year^{-1}) with a pearl millet supply *per capita* of 480 kg inhabitant^{-1} year^{-1}. The weather classification had a low impact on millet production or supply distribution (Figure 2). Out of the explored 5-year period (2016–2020), the last year (2020) reported the largest production (1,144,583 tons) and, consequently, a high supply of pearl millet *per capita* at the national level (130 kg inhabitant^{-1} year^{-1}). From a weather perspective, this year presented low temperatures (average = 28.4°C) and high precipitations (average = 804 mm; LT-HP), both favorable to pearl millet production (Figure 2A). Although 2019 was characterized by high temperatures and low precipitation (HT-LP), more severe weather conditions affecting millet production occurred in the main producing region during 2016 (Figure 2A). The impact of these weather conditions resulted in the lowest average production (616,951 tons) and pearl millet supply *per capita* (67 kg inhabitant^{-1} year^{-1}). During the evaluation period, the average harvested area was 25,325 hectares, increasing by 2,500 hectares between 2016 and 2020. On the other hand, the population increased by roughly 2.8 million during the same period, representing an overall 16% increase.

3.2 Historical weather condition characterization (1990 to 2021)

The overall frequency of the different weather groups over 30 years (1990–2021) was 35% for the HT-LP, while for LT-HP, it was 28% (Supplementary Figure S2). The other weather groups were less frequent (HT-HP = 15% and LT-LP = 22%; Supplementary Figure S2). However, as previously stated for the observed data analysis, the weather classification showed an impact on the simulated pearl millet production. For example, the average reduction of the pearl millet supply in years with HT-LP was approximately 6% (54,858 tons) relative to the average production for the evaluated period (1990 to 2021) in Senegal (Figure 3). In addition, the departments of Louga, Matam, and Tambacounda were identified as potential areas for expanding millet production when adopting the recommended management practices.

3.3 Effect of weather and management practices on millet-based supply of cereal demand: simulated data analysis

The average observed gap between the cereal supply and demand in Senegal between 2016 and 2020 was 3,064,819 tons. The simulated pearl millet production obtained by adopting standard management practices achieved only 22% of the current demand (Figure 3A). The recommended management practices showed the potential to increase the national production of pearl millet to 2,342,490 tons (160% over the current production). This increase in production could reduce the average gap for the analyzed period by 1,441,935 tons, corresponding to 59% of cereal demand for the last 5 years (2016 to 2020; Figure 3B). The northern (e.g., Dagana and

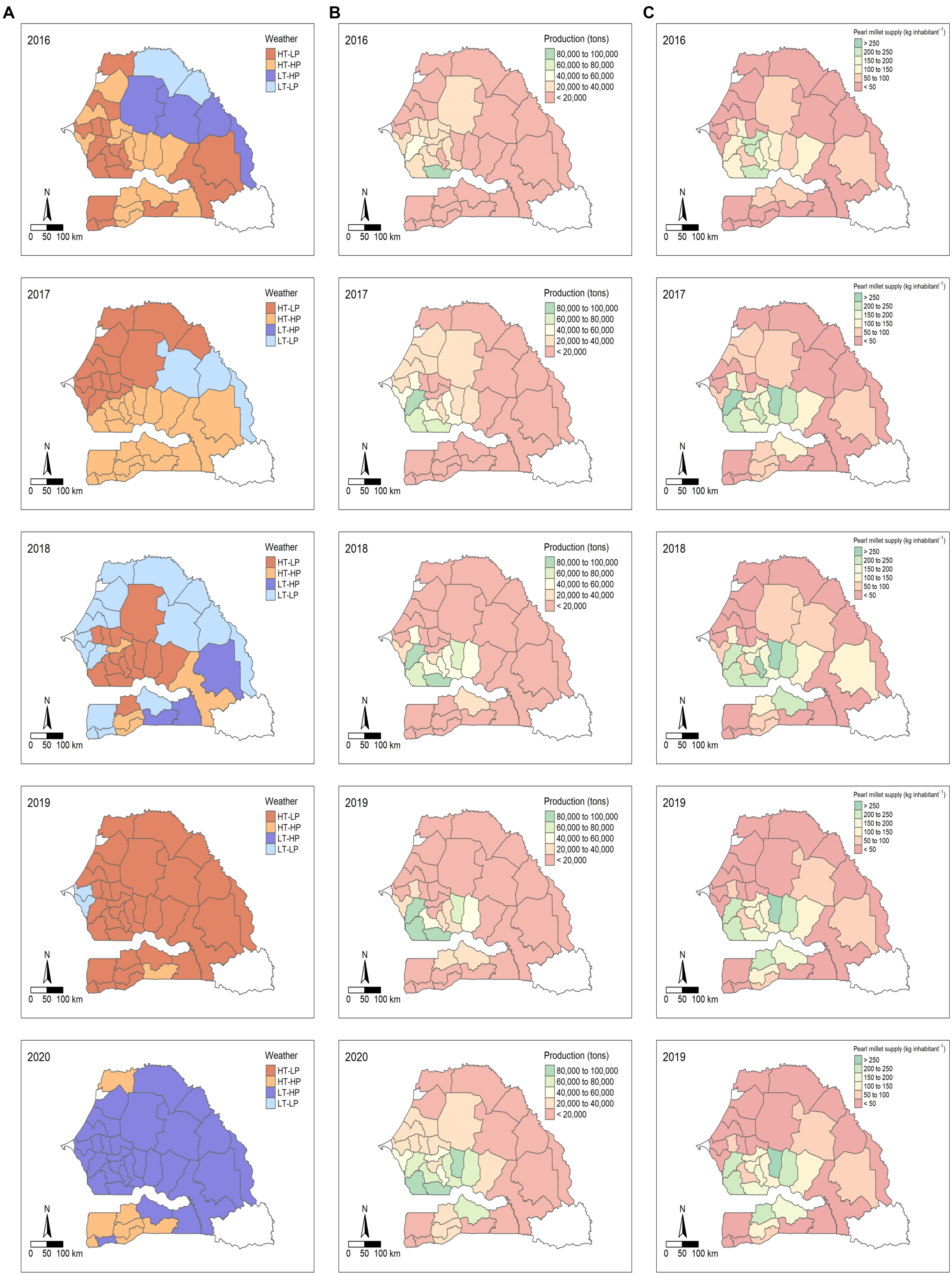

FIGURE 2
Weather characterization (high temperature and low precipitation, HT-LP; high temperature and high precipitation, HT-HP; low temperature and high precipitation, LT-HP; and low temperature and low precipitation, LT-LP); **(A)** and production **(B)** and supply *per capita* of pearl millet **(C)** from 2016 to 2020 at the department level for Senegal.

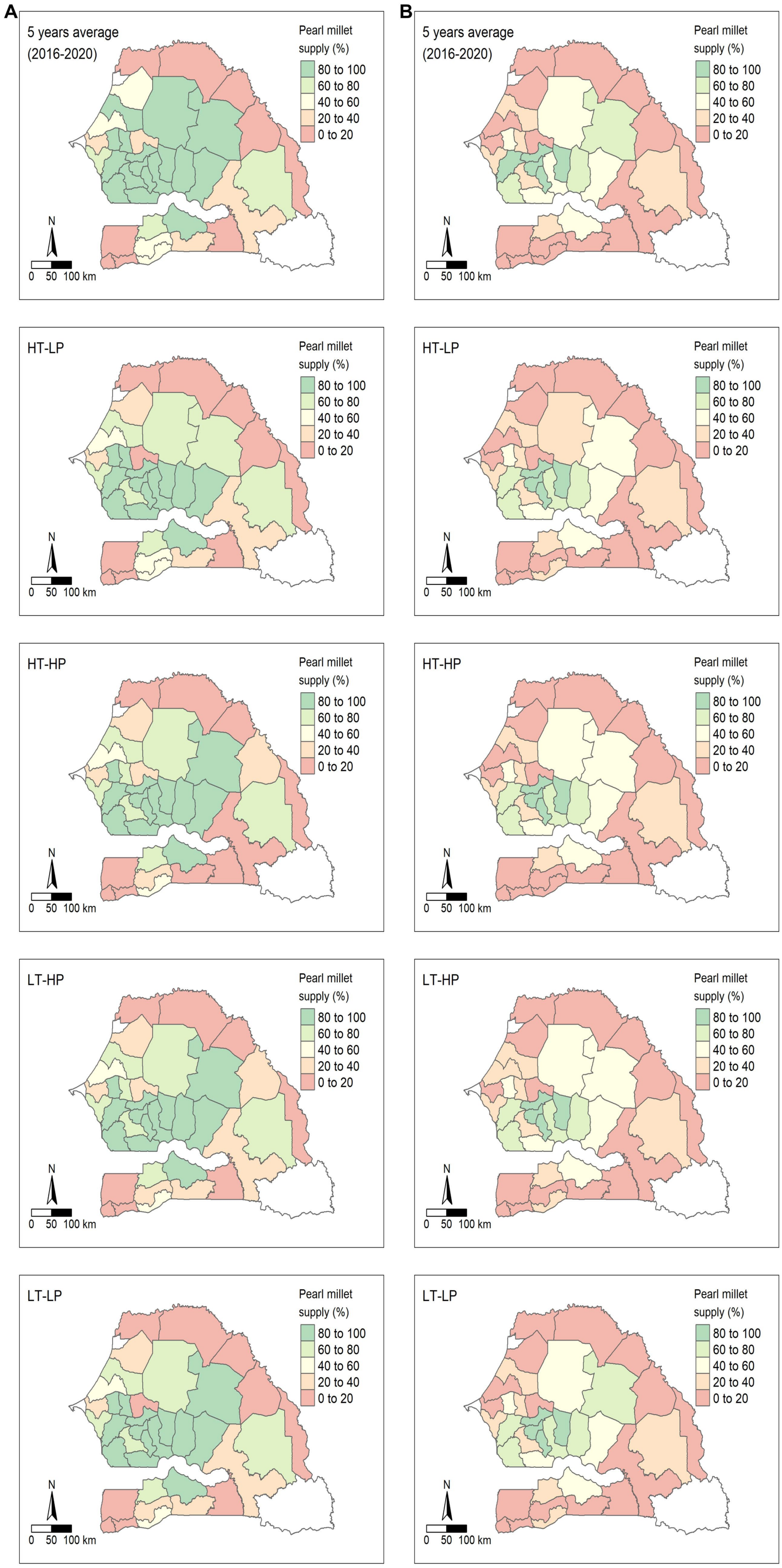

FIGURE 3
Average of pearl millet-based supply of cereal demand (%) for 5 years (2016 to 2021) and for each weather (high temperature and low precipitation, HT-LP; high temperature and high precipitation, HT-HP; low temperature and high precipitation, LT-HP; and low temperature and low precipitation, LT-LP) during the simulated period between 1990 and 2020 at the department level for pearl miller systems adopting the standard **(A)** and recommended **(B)** management in Senegal.

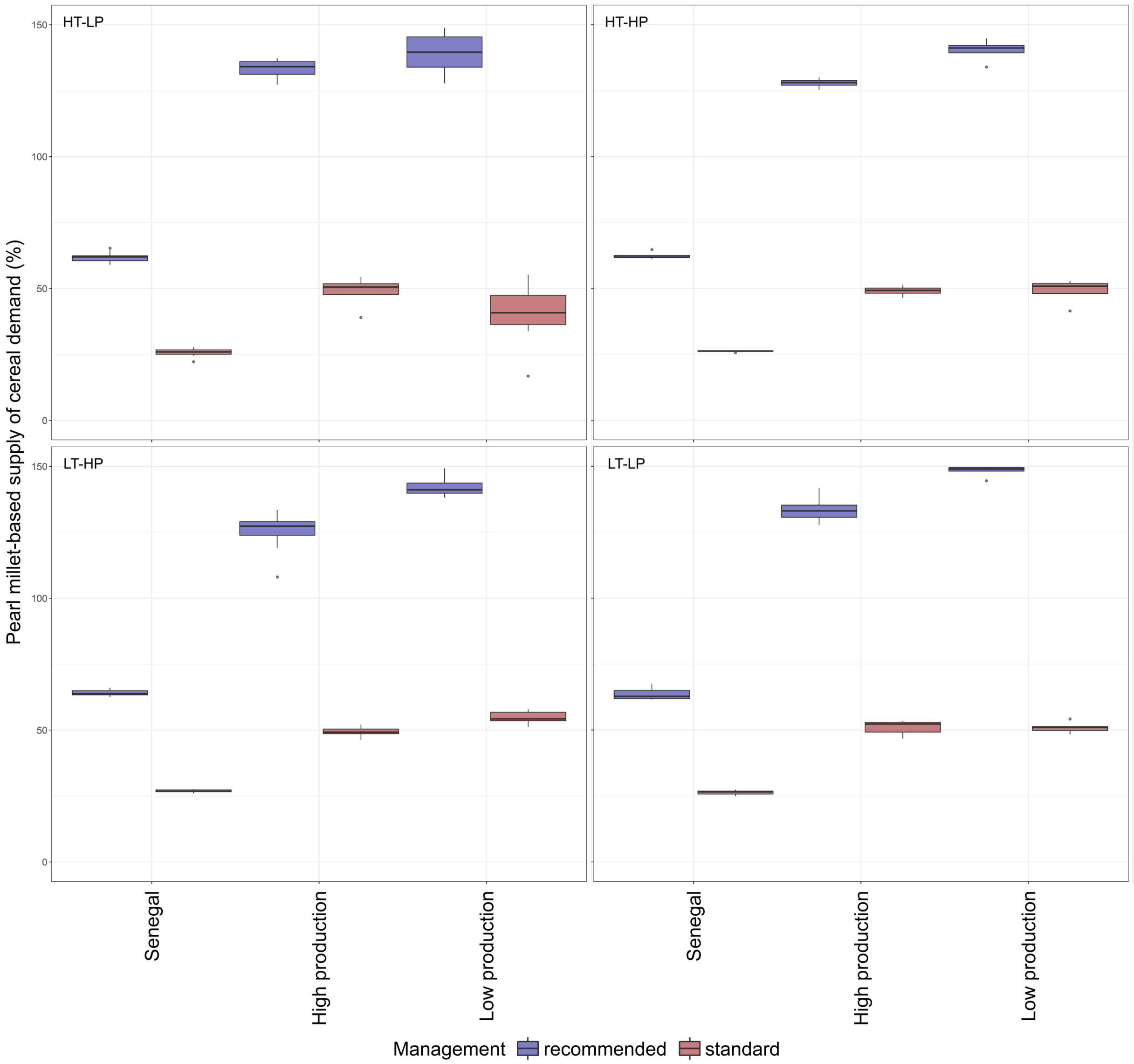

FIGURE 4
Pearl millet-based supply of cereal demand (%) of each weather group (high temperature and low precipitation, HT-LP; high temperature and high precipitation, HT-HP; low temperature and high precipitation, LT-HP; and low temperature and low precipitation, LT-LP) during the period simulated (1990 to 2021) for pearl miller systems adopting the standard and recommended management at the department level in Senegal.

Podor; Supplementary Figure S1) and southern (e.g., Bignona, Oussouye, and Ziguinchor; Supplementary Figure S1) departments showed greater gaps, with the overall pearl millet-based cereal supply remaining below 10%, regardless of the weather conditions and/or recommended management. The harvested area of pearl millet in these departments corresponds to less than 20% of the total area harvested in Senegal (Supplementary Figure S4). The major producing region (central part of the country; Supplementary Figure S4) could exceed its own demands by adopting the recommended management (Figure 3).

The recommended management practices could increase the pearl millet-based supply of cereal demand in departments with different production levels and weather conditions. Two departments with a similar area (~60,000 hectares) but different production levels (Nioro Du Rip = 84,485 tons and Bambey = 40,654 tons) were selected as a case study to evaluate the impact of both management practices and weather conditions. This analysis showed a higher increment in the pearl millet supply in the department with low production (95%; Figure 4) than in the high production department (80%; Figure 3) when employing the recommended management practices. The proportion of pearl millet supply increase in both departments was sufficient to exceed its cereal demands. Nationally, the recommended practices (reporting supply increase by 37%) are not sufficient to meet cereal demand, covering only 62% of cereal demand (Figure 4). The pearl millet-based supply of cereal demand did not present large differences when exploring different weather groups. However, a greater yield variation was documented in the HT-LP group, especially for the low millet-producing department (Figure 4).

3.4 Impact of management practices on pearl millet-based cereal supply (1990 to 2021)

The average supply *per capita* of cereal (observed) from 1990 to 2021 was 162 kg inhabitant^{-1} year^{-1}. Exploring the same period, by adopting standard management (simulated), the pearl millet supply corresponded to 73 kg inhabitant^{-1} year^{-1}, representing 45% of the cereal demand. For the same period and country scale, a gap of 88 kg inhabitant^{-1} year^{-1} was recorded as the difference between supply and the minimum cereal requirement per year (250 kg inhabitant^{-1} year^{-1}). The recommended management practices could increase pearl millet supply *per capita* by up to 102 kg inhabitant^{-1} year^{-1} (140% over the current supply). The simulations showed that between 1990 and 2003, the supply *per capita* obtained by the recommended management adoptions could be greater than the provided all cereals (observed). The average cereal supply *per capita* with the adoption of the recommended management increased by 185% (301 kg inhabitant^{-1} year^{-1}). The minimum requirement was not exceeded only in the last year (2021) of the tested period, mainly due to less favorable weather conditions, such as high temperatures and low precipitation (Figure 5).

4 Discussion

This study provides a current status of the pearl millet-based cereal demand at the department level in Senegal to better understand the major vulnerabilities and facilitate the development of feasible management strategies to reduce food insecurity (Leroy et al., 2015; Diack et al., 2017). To meet the minimum cereal requirement, the current production gap (Fusillier, 1995) could be satisfied by adjusting the management practices of pearl millet systems. In addition, problems related to food accessibility and distribution linked to different socioeconomic, environmental, and production regions (Fanzo, 2018) should be highlighted as major challenges for smallholders to close this food security gap.

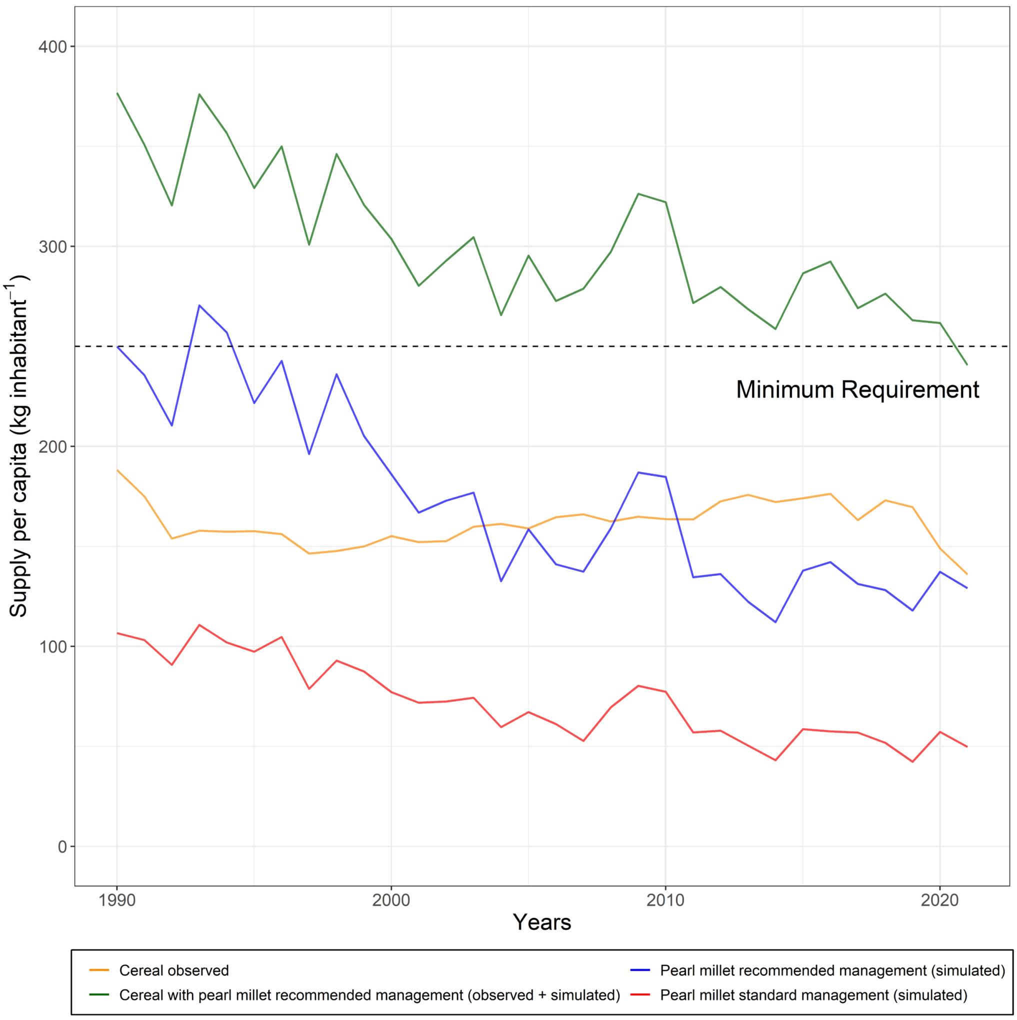

FIGURE 5
Supply *per capita* of cereal (maize, rice, sorghum, and pearl millet observed; solid yellow) considering the simulated recommended management of pearl millet (maize, rice, and sorghum observed + pearl millet simulated; solid green), standard (simulated; dashed red), and recommended (simulated; dashed blue) management of pearl millet and minimum requirement (250 kg inhabitant^{-1} year $^{-1}$; dashed black) for Senegal between 1990 and 2021.

The current pearl millet supply in Senegal relies on rainfed systems, with a water-limited yield potential of 2,200 kg ha^{-1} (Affholder et al., 2013). Several studies have highlighted that better use of inputs (e.g., fertilizers, seed, and herbicides) and water by optimizing planting dates (Araya et al., 2022; Bastos et al., 2022; Vieira Junior et al., 2023) could help avoid the current yield limitations. The current yield potential of pearl millet can be considered relatively low compared with other producing regions of the world (Maman et al., 2003; Dias-Martins et al., 2018; Reddy et al., 2021). The main causes of this low-yield potential are related to poor soil fertility, weed infestation, limited access to inputs (e.g., seeds, fertilizers, and herbicides), and limited availability of labor (Ramaswamy and Sanders, 1992; Affholder, 1994; Zougmoré et al., 2010; Affholder et al., 2013), to mention the most relevant factors. Although inter-annual fluctuation in the subsistence food supply is directly dependent on the weather (Nébié et al., 2021), yield-limiting factors have shown a greater impact on variations in pearl millet production. For example, seasonal precipitation (quantity, intensity, and distribution) is one of the most important weather variables influencing crop production in the Sub-Saharan African region (Guan et al., 2015; Sultan and Gaetani, 2016). However, seasonal precipitation is often insufficient (as a single factor) to explain fluctuations in pearl millet yields (Fall et al., 2021). Effective management practices play a pivotal role in enhancing food security in Senegal. For instance, optimizing the planting date can strategically position the crop within a more conducive period during seasons characterized by high temperatures and low precipitation (Vieira Junior et al., 2023). Additionally, exploring with higher plant densities and employing suitable fertilizers can empower the crop to more effectively tap into its genetic potential (Bastos et al., 2022; Vieira Junior et al., 2023). In this context, it is noteworthy to emphasize that access to fertilizers and other crop inputs is crucial, but closing the gap between the cereal supply and demand will require farmers to combine better crop management with water-saving techniques at both field- and landscape- levels (Zougmoré et al., 2010; Sawadogo, 2011).

Improving pearl millet production, while maintaining its stability over time, is crucial to ensure adequate food security, especially for smallholder-centered food systems (Pucher et al., 2015; Sibhatu and Qaim, 2017; Fanzo, 2018). Previous studies have demonstrated the impact of effective management interventions on increase yields with a more efficient use of the available technologies (Bastos et al., 2022; Vieira Junior et al., 2023). In this sense, this study showed the potential of improved management strategies to increase the overall supply of millet in Senegal. However, as the population continues to grow (Defrance et al., 2020), achieving cereal self-sufficiency will be an elusive target in Senegal. The predominant factor in the decrease of *per capita* food availability in the coming years is high demographic growth, coupled with a less proportionate increase in food production and accessibility (Defrance et al., 2020). Future cereal self-sufficiency will require intensifying the production of other cereals and improving the diversification of current farming systems. In this sense, developing viable and accessible alternatives for farmers will be important to offset the decline of productivity (Trail et al., 2016), minimizing food insecurity for smallholders and their communities in Senegal (Diack et al., 2017).

In addition to the management strategies evaluated in this study, innovative agronomic practices can contribute to the sustainable intensification of cereal production in Sub-Saharan Africa (Kuyah et al., 2021). These practices encompass legume–cereal intercropping (Daryanto et al., 2020; Diatta et al., 2020; Sogoba et al., 2020), agroforestry (Abdoulkadri et al., 2019), and mixed crop–livestock systems (Thornton and Herrero, 2015; Leroux et al., 2022; Akplo et al., 2023). Introducing cereals into mixed cropping or rotation systems with legumes such as pea (*Cajanus cajan*), groundnut (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* (L.) Walp), mung bean (*Vigna radiata*), mucuna (*Mucuna* sp.), and soybean (*Glycine max*) has demonstrated the potential to enhance cereal grain yield and biomass production, offering a valuable dual-purpose approach (Akplo et al., 2023). This type of integrated system not only addresses the essential food and animal product needs of households (Herrero et al., 2010) but also makes efficient use of crop residues for livestock feed (Salmon et al., 2018). The significant benefits associated with the increased millet yield through intercropping align with the recent evidence affirming the positive impact of legumes on nitrogen availability for cereals (Daryanto et al., 2020; Diatta et al., 2020). This effect leads to higher yields even with reduced fertilizer rates (Bastos et al., 2022; Senghor et al., 2023). Conversely, the adverse impact of inter-annual rainfall variability on pearl millet production is evident, with intercropping systems performing suboptimal when compared with the monocropping system in environments characterized by diminished water availability and high temperatures (Senghor et al., 2023). This emphasizes the importance of exercising caution when assuming the universal effectiveness of intercropping as a strategy for adapting to climate variability and underscores the necessity for further research in this domain.

Some key limitations of this study were related to (i) lack of integration of the productive assessment with other factors, such as social, environmental, economic, and human (Stewart et al., 2018; Nébié et al., 2021; Brown et al., 2023), (ii) lack of consideration of more diversified farming systems such as intercropping (Himmelstein et al., 2017) or agricultural livestock systems (Thornton and Herrero, 2015; Leroux et al., 2022) for smallholders in this region, and (iii) improved weather characterization step to account for seasonal variations of temperature and precipitation (quantity, intensity, and distribution) and their impacts on crop productivity (Araya et al., 2022). In the near future, to satisfy the growing cereal demand (Defrance et al., 2020), further research investments should be allocated to extend the approach from pearl millet to other cereals to narrow the gap for cereal self-sufficiency.

5 Conclusion

Critical management interventions can help achieve cereal self-sufficiency but with a need to refocus future research efforts on improving the productivity of more diversified rainfed farming systems in Senegal. Overall, weather variations, represented by different combinations of temperature and precipitation, had a reduced impact, when compared with management, on the overall millet production at the country scale. The recommended management practices increased the pearl millet supply *per capita* up to 102 kg inhabitant^{-1}. This change in supply represents a 2-fold increase, closing the current supply–demand gap (89 kg inhabitant^{-1}) and contributing to the goal of achieving cereal self-sufficiency. However, as the population continues to grow, further technological advancements and efforts on the entire production system are needed to ensure the cereal supply in Senegal. Future cereal self-sufficiency will also require the sustainable intensification of the production of other cereals.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

NV: Conceptualization, Formal analysis, Writing – original draft. AC: Conceptualization, Writing – original draft. DM: Writing – review & editing. AAD: Writing – review & editing. AA: Writing – review & editing. PP: Writing – review & editing. AD: Writing – review & editing. IC: Conceptualization, Supervision, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1281496/full#supplementary-material

References

Abdoulkadri, A., Assoumane, A., Abdou, M. M., Bil-assanou, I. H., Seybou, D. E. H., and Alzouma, Z. M. (2019). Improvement of the productivity of millet (*Pennisetum glaucum* (L.) R. Br.) intercropped with the Arabic gum tree (*Acacia senegal* (L.) Willd.) in agroforestry parkland in Niger. *Adv. Agricult. Sci.* 7, 74–84.

Affholder, F. (1994). *Influence de la fertilisation et du contrôle de l'enherbement sur la réponse des rendements du mil pluvial à un indice hydrique synthétique*. John Libbey Eurotext: Montrouge.

Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E., and Tittonell, P. (2013). The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modelling. *Field Crop Res.* 143, 106–118. doi: 10.1016/j.fcr.2012.10.021

Akplo, T. M., Faye, A., Obour, A., Stewart, Z. P., Min, D., and Prasad, P. V. V. (2023). Dual-purpose crops for grain and fodder to improve nutrition security in semi-arid sub-Saharan Africa: a review. *Food Energy Secur.* 12, 1–7. doi: 10.1002/fes3.492

Araya, A., Jha, P. K., Zambreski, Z., Faye, A., Ciampitti, I. A., Min, D., et al. (2022). Evaluating crop management options for sorghum, pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal. *Clim. Risk Manag.* 36:100436. doi: 10.1016/j.crm.2022.100436

Balboa, G. R., Archontoulis, S. V., Salvagiotti, F., Garcia, F. O., Stewart, W. M., Francisco, E., et al. (2019). A systems-level yield gap assessment of maize-soybean rotation under high- and low-management inputs in the Western US Corn Belt using APSIM. *Agric. Syst.* 174, 145–154. doi: 10.1016/j.agsy.2019.04.008

Bastos, L. M., Faye, A., Stewart, Z. P., Akplo, T. M., Min, D., Prasad, P. V. V., et al. (2022). Variety and management selection to optimize pearl millet yield and profit in Senegal. *Eur. J. Agron.* 139:126565. doi: 10.1016/j.eja.2022.126565

Brown, M. E., Carcedo, A. J. P., Eggen, M., Grace, K. L., Neff, J., and Ciampitti, I. A. (2023). Integrated modeling framework for sustainable agricultural intensification. *Front. Sustain. Food Syst.* 6:1039962. doi: 10.3389/fsufs.2022.1039962

Daryanto, S., Fu, B., Zhao, W., Wang, S., Jacinthe, P. A., and Wang, L. (2020). Ecosystem service provision of grain legume and cereal intercropping in Africa. *Agric. Syst.* 178:102761. doi: 10.1016/j.agsy.2019.102761

Debieu, M., Sine, B., Passot, S., Grondin, A., Akata, E., Gangashetty, P., et al. (2018). Response to early drought stress and identification of QTLs controlling biomass production under drought in pearl millet. *PLoS One* 13:1635. doi: 10.1371/journal.pone.0201635

Defrance, D., Sultan, B., Castets, M., Famien, A. M., and Baron, C. (2020). Impact of climate change in West Africa on cereal production per capita in 2050. *Sustainability (Switzerland)* 12:585. doi: 10.3390/su12187585

Diack, M., Loum, M., Diop, C. T., Holloway, A., and Berger, G. (2017). Jàmbá-journal of disaster risk. *Studies*. 9:a379. doi: 10.4102/jamba

Dias-Martins, A. M., Pessanha, K. L. F., Pacheco, S., Rodrigues, J. A. S., and Carvalho, C. W. P. (2018). Potential use of pearl millet (*Pennisetum glaucum* (L.) R. Br.) in Brazil: food security, processing, health benefits and nutritional products. *Food Res. Int.* 109, 175–186. doi: 10.1016/j.foodres.2018.04.023

Diatta, A. A., Abaye, O., Thomason, W. E., Lo, M., Thompson, T. L., Vaughan, L. J., et al. (2020). Evaluating pearl millet and mungbean intercropping in the semi-arid regions of Senegal. *Agron. J.* 112, 4451–4466. doi: 10.1002/agj2.20341

Direction de l'Analyse,de la Prévision et desStatistiques Agricoles (DAPSA). (2022). *Résumé exécutif L'Enquête Agricole Annuelle (EAA) est la principale enquête par sondage d'envergure nationale permettant*. Available at: https://www.dapsa.gouv.sn/ (Accessed December 21, 2023).

Fall, C. M. N., Lavaysse, C., Kerdiles, H., Dramé, M. S., Roudier, P., and Gaye, A. T. (2021). Performance of dry and wet spells combined with remote sensing indicators for crop yield prediction in Senegal. *Clim. Risk Manag.* 33:331. doi: 10.1016/j.crm.2021.100331

Fanzo, J. (2018). The role of farming and rural development as central to our diets. *Physiol. Behav.* 193, 291–297. doi: 10.1016/j.physbeh.2018.05.014

Funk, C., Verdin, A., Michaelsen, J., Peterson, P., Pedreros, D., and Husak, G. (2015). A global satellite-assisted precipitation climatology. *Earth Syst Sci Data* 7, 275–287. doi: 10.5194/essd-7-275-2015

Fusillier, J.-L. (1995). *Bilan et perspectives de diffusion de la maisiculture en zone de savane d'Afrique de l'Ouest*. In: Production et valorisation du maïs à l'échelon villageois en Afrique de l'Ouest: actes du séminaire "Maïs prospère", 25-28 janvier 1994, Cotonou, Bénin. Montpellier:CIRAD-SAR, UNB-FSA. 29–40.

Godfray, C. H. J., J. R. Beddington, Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: The challenge of feeding 9 billion people. Available at: http://science.sciencemag.org/ (Accessed August 22, 2023)

Gowda, N. A. N., Siliveru, K., Vara Prasad, P. V., Bhatt, Y., Netravati, B. P., and Gurikar, C. (2022). Modern processing of Indian millets: a perspective on changes in nutritional properties. *Foods* 11:499. doi: 10.3390/foods11040499

Guan, K., Sultan, B., Biasutti, M., Baron, C., and Lobell, D. B. (2015). What aspects of future rainfall changes matter for crop yields in West Africa? *Geophys. Res. Lett.* 42, 8001–8010. doi: 10.1002/2015GL063877

Hengl, T., De Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B. M., Ribeiro, E., et al. (2014). SoilGrids1km – global soil information based on automated mapping. *PLoS One* 9:5992. doi: 10.1371/journal.pone.0105992

Herrero, M., Thornton, P. K., Notenbaert, A. M., Wood, S., Msangi, S., Freeman, H. A., et al. (2010). Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 1979, 822–825. doi: 10.1126/science.1183725

Himmelstein, J., Ares, A., Gallagher, D., and Myers, J. (2017). A meta-analysis of intercropping in Africa: impacts on crop yield, farmer income, and integrated pest management effects. *Int. J. Agric. Sustain.* 15, 1–10. doi: 10.1080/14735903.2016.1242332

Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., et al. (2014). APSIM – evolution towards a new generation of agricultural systems simulation. *Environ. Model. Softw.* 62, 327–350. doi: 10.1016/j.envsoft.2014.07.009

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change 2007: The physical science basis: Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Kothari, S. I., Kumar, S., Vishnoi, R. K., Kothari, A., and Watanabe, K. N. (2005). Applications of biotechnology for improvement of millet crops: review of progress and future prospects. *Plant Biotechnol.* 22, 81–88. doi: 10.5511/plantbiotechnology.22.81

Kuyah, S., Weldesemayat Sileshi, G., Nkurunziza, L., Chirinda, N., Celestin Ndayisaba, P., Dimobe, K., et al. (2021). Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. *Agron. Sustain. Dev.* 41, 1–21. doi: 10.1007/s13593-021-00673-4/Published

Leroux, L., Faye, N. F., Jahel, C., Falconnier, G. N., Diouf, A. A., Ndao, B., et al. (2022). Exploring the agricultural landscape diversity-food security nexus: an analysis in two contrasted parklands of Central Senegal. *Agric. Syst.* 196:3312. doi: 10.1016/j.agsy.2021.103312

Leroy, J. L., Ruel, M., Frongillo, E. A., Harris, J., and Ballard, T. J. (2015). Measuring the food access dimension of food security: a critical review and mapping of indicators. *Food Nutr. Bull.* 36, 167–195. doi: 10.1177/0379572115587274

Maman, N., Lyon, D. J., Mason, S. C., Galusha, T. D., and Higgins, R. (2003). Pearl millet and grain Sorghum yield response to water supply in Nebraska. *Agron. J.* 95:1624. doi: 10.2134/agronj2003.1618

McKenzie, F. C., and Williams, J. (2015). Sustainable food production: constraints, challenges and choices by 2050. *Food Secur.* 7, 221–233. doi: 10.1007/s12571-015-0441-1

Miguez, Fernando. (2022). Apsimx: Inspect, read, edit and run 'APSIM' "next generation" and 'APSIM' classic. R package version 2.3.1. Available at: https://CRAN.R-project.org/package=apsimx

Nébié, E. K. I., Ba, D., and Giannini, A. (2021). Food security and climate shocks in Senegal: who and where are the most vulnerable households? *Glob. Food Sec.* 29:100513. doi: 10.1016/j.gfs.2021.100513

Opole, R. A. (2019). Opportunities for enhancing production, utilization and marketing of finger millet in Africa. *Afr. J. Food Agric. Nutr. Dev.* 19, 13863–13882. doi: 10.18697/AJFAND.84.BLFB1004

Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., et al. (2021). SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil* 7, 217–240. doi: 10.5194/soil-7-217-2021

Prasad, P. V. V., Bheemanahalli, R., and Jagadish, S. V. K. (2017). Field crops and the fear of heat stress—opportunities, challenges and future directions. *Field Crop Res.* 200, 114–121. doi: 10.1016/j.fcr.2016.09.024

Pucher, A., Sy, O., Angarawai, I. I., Gondah, J., Zangre, R., Ouedraogo, M., et al. (2015). Agro-morphological characterization of west and central African pearl millet accessions. *Crop Sci.* 55, 737–748. doi: 10.2135/cropsci2014.06.0450

R Core Team. (2021). R: A language and environment for statistical computing. R. Found. Stat. Comput. Available at: https://www.R-project.org/ (Accessed December 21, 2023).

Ramaswamy, S., and Sanders, J. H. (1992). Population pressure, land degradation and sustainable agricultural Technologies in the Sahel. *Agric. Syst.* 40, 361–378. doi: 10.1016/0308-521X(92)90047-R

Rasmussen, K., D'haen, S., Fensholt, R., Fog, B., Horion, S., Nielsen, J. O., et al. (2016). Environmental change in the Sahel: reconciling contrasting evidence and interpretations. *Reg. Environ. Chang.* 16, 673–680. doi: 10.1007/s10113-015-0778-1

Reddy, P. S., Satyavathi, C. T., Khandelwal, V., Patil, H. T., Gupta, P. C., Sharma, L. D., et al. (2021). Performance and stability of pearl millet varieties for grain yield and micronutrients in arid and semi-arid regions of India. *Front. Plant Sci.* 12:201. doi: 10.3389/fpls.2021.670201

Rukuni, M., and Kellogg, W. K. (2002). Symposium: Feeding the world in the coming decades Africa: Addressing growing threats to food security 1. Available at: https://academic.oup.com/jn/article/132/11/3443S/4687226 (Accessed August 22, 2023)

Salmon, G., Teufel, N., Baltenweck, I., van Wijk, M., Claessens, L., and Marshall, K. (2018). Trade-offs in livestock development at farm level: different actors with different objectives. *Glob. Food Sec.* 17, 103–112. doi: 10.1016/j.gfs.2018.04.002

Sawadogo, H. (2011). Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. *Int. J. Agric. Sustain.* 9, 120–128. doi: 10.3763/ijas.2010.0552

Senghor, Y., Balde, A. B., Manga, A. G. B., Affholder, F., Letourmy, P., Bassene, C., et al. (2023). Intercropping millet with low-density cowpea improves millet productivity for low and medium N input in semi-arid Central Senegal. *Heliyon* 9:e17680. doi: 10.1016/j.heliyon.2023.e17680

Sibhatu, K. T., and Qaim, M. (2017). Rural food security, subsistence agriculture, and seasonality. *PLoS One* 12:6406. doi: 10.1371/journal.pone.0186406

Sogoba, B., Traoré, B., Safia, A., Samaké, O. B., Dembélé, G., Diallo, S., et al. (2020). On-farm evaluation on yield and economic performance of cereal-cowpea intercropping to support the smallholder farming system in the Soudano-Sahelian zone of Mali. *Agriculture (Switzerland)* 10, 1–15. doi: 10.3390/agriculture10060214

Sparks, A. (2018). Nasapower: a NASA POWER global meteorology, surface solar energy and climatology data client for R. *J. Open Source Softw.* 3:1035. doi: 10.21105/joss.01035

Stewart, Z. P., Middendorf, B. J., and Prasad, V. (2018). Sustainable intensification assessment framework online toolkit. Available at: https://hdl.handle.net/10568/103782 (Accessed August 22, 2023)

Sultan, B., and Gaetani, M. (2016). Agriculture in West Africa in the twenty-first century: climate change and impacts scenarios, and potential for adaptation. *Front. Plant Sci.* 7:1262. doi: 10.3389/fpls.2016.01262

Thornton, P. K., and Herrero, M. (2015). Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nat. Clim. Chang.* 5, 830–836. doi: 10.1038/nclimate2754

Tilman, D., Balzer, C., Hill, J., and Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 108, 20260–20264. doi: 10.1073/pnas.1116437108

Trail, P., Abaye, O., Thomason, W. E., Thompson, T. L., Gueye, F., Diedhiou, I., et al. (2016). Evaluating intercropping (living cover) and mulching (desiccated cover) practices for increasing millet yields in Senegal. *Agron. J.* 108, 1742–1752. doi: 10.2134/agronj2015.0422

Ullah, A., Ahmad, A., Khaliq, T., and Akhtar, J. (2017). Recognizing production options for pearl millet in Pakistan under changing climate scenarios. *J. Integr. Agric.* 16, 762–773. doi: 10.1016/S2095-3119(16)61450-8

Vadez, V., Hash, T., Bidinger, F. R., and Kholova, J. (2012). II.1.5 phenotyping pearl millet for adaptation to drought. *Front. Physiol.* 3:386. doi: 10.3389/fphys.2012.00386

van den Broeck, G., Van Hoyweghen, K., and Maertens, M. (2018). Horticultural exports and food security in Senegal. *Glob. Food Sec.* 17, 162–171. doi: 10.1016/j.gfs.2017.12.002

van Oosterom, E. J., Carberry, P. S., and O'leary, G. J. (2001a). Simulating growth, development, and yield of tillering pearl millet I. Leaf area profiles on main shoots and tillers. *Field Crop Res.* 72, 51–66. doi: 10.1016/S0378-4290(01)00164-2

van Oosterom, E. J., O'leary, G. J., Carberry, P. S., Craufurd, P. Q., Au, E. J., and Van, O. (2001b). Simulating growth, development, and yield of tillering pearl millet II. Simulation of canopy development. *Field Crop Res.* 72, 67–91. doi: 10.1016/S0378-4290(01)00165-4

van Oosterom, E. J., O'leary, G. J., Carberry, P. S., Craufurd, P. Q., Au, E. J., and Van, O. (2002). Simulating growth, development, and yield of tillering pearl millet. III. Biomass accumulation and partitioning. *Field Crop Res.* 79, 85–106. doi: 10.1016/S0378-4290(02)00156-9

Vieira Junior, N., Carcedo, A. J. P., Min, D., Diatta, A. A., Araya, A., Prasad, P. V. V., et al. (2023). Management adaptations for water-limited pearl millet systems in Senegal. *Agric. Water Manag.* 278:108173. doi: 10.1016/j.agwat.2023.108173

Wheeler, T., and von Braun, J. (2013). Climate change impacts on global food security. *Science* 341, 508–513. doi: 10.1126/science.1239402

Zhou, Y., and Staatz, J. (2016). Projected demand and supply for various foods in West Africa: implications for investments and food policy. *Food Policy* 61, 198–212. doi: 10.1016/j.foodpol.2016.04.002

Zougmoré, R., Mando, A., and Stroosnijder, L. (2010). Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso. *Nutr. Cycl. Agroecosyst.* 88, 17–27. doi: 10.1007/s10705-008-9191-1