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Assessment of the relations between crop yield variability and the onset and intensity of the West African Monsoon

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ABSTRACT

Timely information on the onset of rain is essential for effectively adapting to climate variability and increasing the resilience of rain-fed systems. However, defining optimal sowing dates based on the onset of rain has been challenging. We compared and analyzed the West African Monsoon onset according to Raman's, modified Sivakumar's, Yamada's, and Liebmann's definitions using station data from 13 locations in Senegal from 1981 to 2020. Subsequently, we systematically analyzed the effect of the differently estimated monsoon onsets(WAM-OS) on maize development. To this end, we applied the set of the generated WAM-OS as sowing dates in simulations of maize growth and yields, applying the Agricultural Production Systems sIMulator(APSIM) at 13 locations representing different agroclimatic regions across Senegal. We examined the impact of the sowing dates under variable conditions of soil organic carbon(SOC) and plant available water capacity(PAWC). Our analysis showed statistically significant differences between the WAM-OS dates, rainfall characteristics computed for these, and maize yields simulated using different sowing dates according to the WAM-OS definitions. We found Liebmann's onset dates were most suitable for both hydrological and agronomic applications since they were characterized by the lowest probabilities of prolonged dry spells after onset, the highest amount of rainfall in the mid-season, and the highest simulated maize yields compared to other onset definitions. Our results highlight the importance of sowing dates and their accurate prediction for improving crop productivity in the study area. We also found SOC and PAWC were important factors that improved maize yields. We recommend improved access to climate information services to help smallholder farmers get timely information that helps them in their sowing decisions and encourage agronomic interventions that improve the SOC level, soil pore volume to retain more water and other soil properties directly(e.g., tillage) and indirectly(suited cropping systems) that contribute to enhancing crop productivity.

1. Introduction

1.1. Background

Climate change and variability accelerate food insecurity, hunger, and poverty among smallholder farmers who mainly depend on rain for crop production (Ahmed et al., 2021; Mertz et al., 2008). High inter-annual variation in rainfall characteristics such as onset and cessation dates, length of the growing period, probability of mid-season breaks, and frequency of extreme events constrains on-farm key operations such as sowing and other tactical management such as fertilizer applications during the season. This results in poor planning and management of agricultural activities during the growing season which, in turn, often leads to poor crop productivity, and low yield quality and

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quantity (Krell et al., 2022).

In the Sahel, efficient and timely crop planning is crucial to maximize crop production, adapt to climate variability, and increase the sustainability and resilience of the production systems. Smallholder farmers usually plan and anticipate possible interventions during the season based on the actual onset of the monsoon— Similar to previous studies (Gbode et al., 2021; Niang et al., 2020), here the word monsoon is used to refer to the rainy season of the year, i.e., May to October. However, their knowledge to define and predict the monsoon onset is limited to traditional methods such as the flowering of some trees, the appearance of specific insects, the speed and direction of winds, etc., (Agbodan et al., 2020; Elia et al., 2014) whose predictive skill decreases significantly with a recent increase in both temperature and rainfall variability in the region (Ahmed et al., 2021; Mertz et al., 2008; Nouaceur and Murarescu, 2021; Porkka et al., 2021). Thus, the most accurate method of defining the monsoon onset is desirable because the monsoon onset has become a key driver of food security and livelihood for smallholder farmers (Krell et al., 2022).

Since the 1970s, researchers have produced more than 18 definitions—from local to regional scale—to define the start of the monsoon in the Sahel region (Fitzpatrick et al., 2015). On the other hand, farmers in different communities in the region have their onset definitions—agronomic onset definitions—on which they base their decisions. Having several definitions without information about their relative advantage makes it difficult to choose the best sowing date. To address the problem, studies have investigated the correlation between the available agronomic and meteorological onset definitions (Dunning et al., 2018; Fitzpatrick et al., 2015) aiming to establish optimum planting windows that reduce production risks associated with the time of planting (Akinseye et al., 2015). However, it will be paramount to perform location-specific comprehensive analyses of the hydrological and agronomic impacts of the available onset date definitions. Outcomes from such analyses will provide crucial information for improving resilience and sustainability in rainfed systems for a given location/region.

Traditionally, smallholder farmers may sow their crops when they perceive that the rainy season has started mostly after receiving the first rain or a few days after the first rain (Lamega et al., 2021; Stern et al., 1981). The reliability of such kind of practices has been decreasing due to the increasing frequency of false starts which are often followed by prolonged dry spells after the first rains (Porkka et al., 2021) which create crop water stresses that, depending on their severity and timing, lead to failure or poor germination of the planted seeds (Krell et al., 2022). Therefore, the optimum sowing date should be characterized by a low probability of occurrence of long dry spells after sowing and has a higher probability of receiving continuous rainfall to accumulate enough soil moisture for germination, crop growth, and yield formation (Rötter and Van Keulen, 1997; Vega et al., 2020).

1.2. Objectives

The present study aims to examine the inter-annual variability of maize yields over 40 years (1981 – 2020) simulated by a crop growth model as affected by the sowing dates generated each year using a set of four different monsoon onset definitions and to establish the most relevant definition(s) to guide agronomic activities in the study area. Although the number of West African monsoon onset definitions has significantly increased recently, an updated assessment of their suitability to guide on-farm decisions, in particular for crop planning and management, has not been done to our knowledge. For this purpose, the study compared and analyzed the West African Monsoon (WAM) onset dates according to Raman's (Raman, 1974), modified Sivakumar's (Sivakumar, 1988), Yamada's (Yamada et al., 2013), and Liebmann's (Dunning et al., 2016), definitions using station data from 13 locations in Senegal from 1981 to 2020. The four definitions were considered most appropriate for the study's objectives because they required daily rainfall as the primary input, making them easier to evaluate in a process-based crop model (further details on the choice of the four definitions are found in the methods section). Subsequently, we applied the set of the generated onset dates according to the four definitions as sowing dates in simulations of maize growth and yields using the Agricultural Production Systems sIMulator (APSIM). It should be noted that maize production is rare in the northern part of the country (Hernández et al., 2021). However, the present study used maize as a test crop to investigate the impact of sowing dates influenced by monsoon onset on crop growth and productivity. The simulated inter-annual maize yield variabilities associated with sowing dates were examined and based on our results we suggested the most relevant onset definition for the study area.

2. Material and methods

2.1. Study location and dataset

The study area consists of 13 locations from Senegal districts (12 to 14° N, 17 to 10° W) distributed across major climatic zones in Senegal. Depending on the amount of annual rainfall received in a particular zone, Senegal is normally divided into six climatic zones i.e. (i) Guinean (>1000 mm/y), (ii) Soudano-Guinean (800 – 1000 mm/y), (iii) Soudanian (600 – 800 mm/y), (iv) Soudano-Sahelian (500 – 600 mm/y), (v) Sahel-Soudanian (300 – 500 mm/y), and (vi) Sahelian (<300 mm/y) (Mertz et al., 2008). In the present study we regrouped the aforementioned climatic zones into four major groups i.e. (i) Soudanian-Guinean (>700 mm/y), (ii) Soudano- Sahelian (500 – 700 mm/y), (iii) Sahelian-Soudanian (350 –500 mm/y), and (iv) Sahelian (<350 mm/y) as shown in Fig. 1. Regrouping was based on the water requirements of maize per season to suit the purpose of the present study i.e., simulating how seasonal rainfall onset and distribution impacts simulated maize yields under a different set of agronomic practices such as sowing dates, and soil moisture and nutrients conditions. The threshold of the rainfall amount in the driest zone i.e., Sahelian, was 22% less than 450 mm whereby 22% was the 20th percentile of the average CV (22%) and 450 mm was regarded as the minimum water requirements of cereal crops in semi-arid per season (Moeletsi and Walker, 2012).

The 13 locations used in the present study were selected to represent the aforementioned climatic zones. In the following, abbreviations have been used to represent the aforementioned climatic zones: Sou-Gui (Soudanian-Guinean), Sou-Sah (Soudano- Sahelian), Sah-Sou (Sahelian-Soudanian), and Sah (Sahelian).

Daily rainfall data from 1981 to 2020 in all the locations were obtained from the National Agency of Civil Aviation and Meteorology—Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM). Daily maximum and minimum temperature data were obtained from ERA5—the fifth generation ECMWF atmospheric reanalysis of the global climate at 0.25° x 0.25° resolution. Solar radiation values were computed using the Donatelli-Campbell model (Donatelli et al., 1998) which requires daily maximum and minimum temperatures, daily rainfall records, and the latitude of the location whose solar radiation is to be computed.

2.2. Methods for assessing rainfall trends and variability

The distribution and variability of annual and seasonal rainfall amount and the number of rainy days in the study locations were analyzed and compared using various numerical measures i.e., average, coefficient of variation, percentiles, and probability of exceedance. A rainy day is defined as a day that receives at least 1 mm (World Meteorological Organization, 2017). Average and coefficient of variation (CV) were used to characterize temporal variability and to measure the amount of dispersion respectively in the annual and seasonal rainfall amounts. Moreover, we used analysis of variance (ANOVA) to determine whether there were significant differences between the means of the

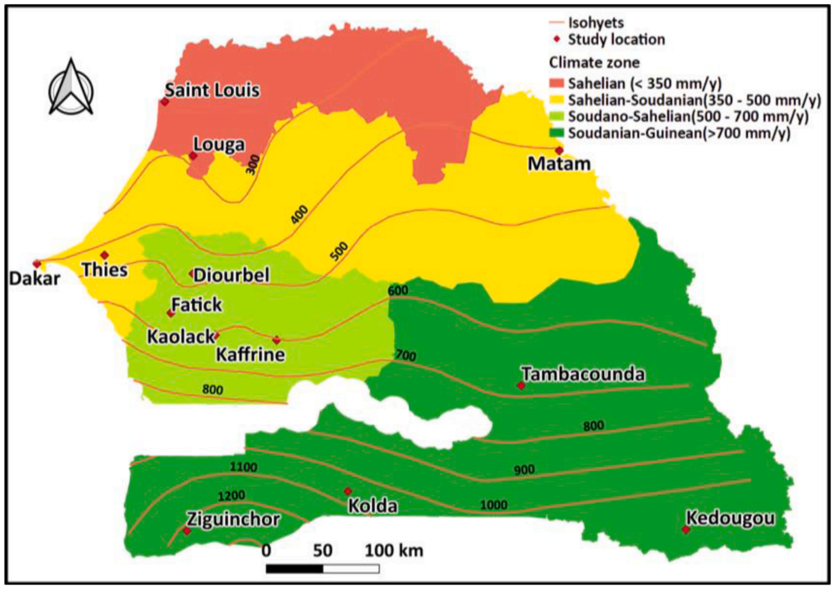

Fig. 1. The map of Senegal showing locations in different rainfall zones in the study area. The average annual rainfall on which the "climate zonation" was based was computed for the period 1981 – 2020.

amount of seasonal rainfall and simulated maize yields in different locations in the study area. Trends in seasonal and annual rainfall amounts and the number of rainy days were computed using the Mann-Kendall test—a non-parametric test that determines increasing or decreasing trends in a monotonic series. It tests the hypotheses (i) Null hypothesis: there is no trend in the time series (ii) Alternative hypothesis: there is either a decreasing or increasing trend in the time series (Gocic & Trajkovic, 2013). One advantage of the Mann-Kendall is that as a non-parametric test, it does not require the series to be normally distributed or linear. The Mann-Kendall test has been proven for its suitability to detect increasing and decreasing trends in climate and environmental data (Alemu & Dioha, 2020) and dependable test for identifying trends in time series rainfall data sets (Bari et al., 2016; Bora et al., 2022; Sharma and Saha, 2017; Tiwari and Pandey, 2018).

2.3. The onset of the West African Monsoon in the study area

The West African Monsoon (WAM) accounts for up to 90% of the total annual rainfall in the Sahel region. Its growth and development are accompanied by complex atmospheric processes which vary spatially and temporally over the region (Geen et al., 2020; Sultan and Janicot, 2003) a fact that makes it difficult to precisely define the onset of the WAM. As a result, there are more than 18 definitions, available in the literature, of the WAM onset both in the local and regional context (Fitzpatrick et al., 2015). Local definitions are more relevant to agricultural activities, and they have been used widely in making crucial agronomic decisions during the growing period. These definitions consider various inputs such as relative humidity, Outgoing Longwave Radiation (OLR), and rainfall at different scales e.g., daily, pentad, and monthly. The present study selected four local definitions among the onset definition available in the literature (Dunning et al., 2016; Fitzpatrick et al., 2015; Raman, 1974) that take daily rainfall as input to define the onset of the monsoon to assess their suitability to simulate crop growth using the APSIM crop model which also requires rainfall data as input at daily time-step. The study then analyzed and compared the following four local WAM onset definitions:

Raman's definition (D_1)

Raman defined the onset of monsoon as the first occasion the 7-day total exceeds 25 mm and includes at least 4 rainy days (Raman, 1974). The definition was first applied in India to describe the onset of the Indian Monsoon in the Maharashtra State. However, due to its relevance and applicability, it has been adopted and used to define the onset of various monsoons including the WAM (Bekele et al., 2017; Quagraine et al., 2017).

Modified Sivakumar's definition (D_2)

The National Agency of Civil Aviation and Meteorology (ANACIM) modified the original Sivakumar's onset definition (Sivakumar, 1988) by setting two different rainfall thresholds one for the northern part of the country and the other for the central and southern parts of the country. The modified definition which is currently used by ANACIM defines the onset date as the first occasion with more than X *mm* in 3 days after 1st May and no dry spell of 20 days or more within the following 30 days where $X = 15$ *mm* in the northern parts (Sahelian and Sahelian-Soudanian climatic zones) and $X = 20$ *mm* in the central and southern parts (Soudanian- Sahelian and Soudanian-Guinean climatic zones).

Yamada's definition (D_3)

According to Yamada's definition, the onset date is the date when the 6-day average rainfall exceeds 2 mm (Yamada et al., al.,2013).

Modified Liebmann's definition (D_4)

Is the first day after the dry period in which the daily rainfall is above the climatological mean daily rainfall (Dunning et al., 2016). The details on the mathematical approach of definition are provided in the supplementary materials.

2.4. Process-based modeling of crop growth and yield

We aimed to assess the impacts of sowing a high water-demand cereal crop i.e. maize on the onset dates defined by the four definitions. To this end, we set up a simulation run in the Agricultural Production Systems sIMulator (APSIM version 7.8) maize module to simulate maize growth and yields. We created a sowing module in APSIM that is capable of sowing each year using a different sowing date criterion which enabled APSIM to use different sowing dates each year generated by the four definitions. The four sets of sowing dates were tested under different soil conditions i.e. plant available water capacity (PAWC) and amount of organic soil carbon. We used three levels of PAWC—low (55.4 mm), medium (83.1 mm), and high (110.8 mm)—and three levels of soil organic carbon— 0.56%, 1.12%, and 2.10% in the topsoil (0 to 30 cm depth) which made a poor, average, and good fertility soil profile respectively. Both soil nitrogen and surface organic matter were reset each year on the 1st of April. A medium-duration cultivar (Dekalb XL82)—90 to 120 days to maturity—was used. Nitrogen fertilizer of 40 kg/ha N was applied—50% at sowing and 50% 30 days after sowing. The maize plant population was 40,000 plants per hectare. A factorial simulation was designed in the four climatic zones using different soil conditions (PAWC and soil organic carbon levels) and sowing dates.

APSIM combines a set of management modules to simulate various biological and physical processes in farming systems. It takes soil, climate, and agronomic management variables as input to simulate crop growth and development (Holzworth et al. 2014). Input data APSIM, i.e., a range of soil properties, weather, and agronomic management variables interact in various ecophysiological processes above- and below-ground related to the crop-soil-atmosphere interface and its subsystems. The interactions of genotype by environment and management (G x E x M) are simulated on a daily time step (Mandrini et al., 2022). APSIM model has been developed (Keating et al., 2003) and widely tested in subhumid semi-arid environments of Africa to simulate the performance of various cereal and legume crops under different farming systems (Whitbread et al., 2010; Akinseye et al. 2017; Hoffmann et al., 2020; Nelson et al., 2022).

3. Results

3.1. Rainfall distribution, trends, and variability

3.1.1. Annual and seasonal rainfall variability in the study locations

The amount and frequency of annual and seasonal rainfall in the study locations significantly differed from one rainfall zone to the other. The Sah and Sah-Sou locations i.e., Dakar, Louga, Matam, St. Louis, and Thies, received the lowest amount of rainfall compared to other climatic zones in the study area. The highest mean annual rainfall in the aforementioned zones was received in Thies (444 mm) and the lowest in St. Louis (262 mm). The Sou- Sah locations i.e., Diourbel, Fatick, Kaffrine, and Kaolack received a higher amount of rainfall (at least 500 mm/year) as compared to both Sah and Sah-Sou locations. The highest amounts of rainfall—at least 700 mm annual mean rainfall—were received in the Sou-Gui locations i.e., Kedougou, Kolda, Tambacounda, and Ziguinchor. The mean annual number of rainy days was less than 45 in both Sah, Sah-Sou, and Sou-Sah locations, and ranged from 48 to 72 rainy days in the Sou-Gui locations (Table S1 in supplementary materials).

The inter-annual rainfall variability is relatively high in all locations—with CV >20% except in Kedougou where the CV is less than 20%—, however, the variation in the number of rainy days is moderate (CV <20%) in most of the locations (Table S1). Similar to annual rainfall, the amount of seasonal rainfall is higher in Soudanian-Guinean locations as compared to Sah-Sou and Sou-Sah locations. Also, the absolute variability in seasonal rainfall, i.e., in rainfall amounts, is higher in most of the locations than that for the number of rainy days.

The probability of exceedance charts in Fig. 2a, 2 b, 2 c, and 2 d, characterize seasonal rainfall distribution and the possible crop production risks associated with rainfall in the study area. In the Sah and Sah-Sou locations (Fig. 2a and b), the probability of getting at least 450 mm (note: 450 mm is a minimum water requirement for cereal crops such as maize in the semi-arid environment (Moeletsi and Walker, 2012) of rain per season is very low (less than 50%). The farmers in rain-fed systems in the aforementioned climatic zones are at a higher risk of losing their investment due to frequent crop failure caused by the erratic nature of the seasonal rainfall in their production environment. Contrary

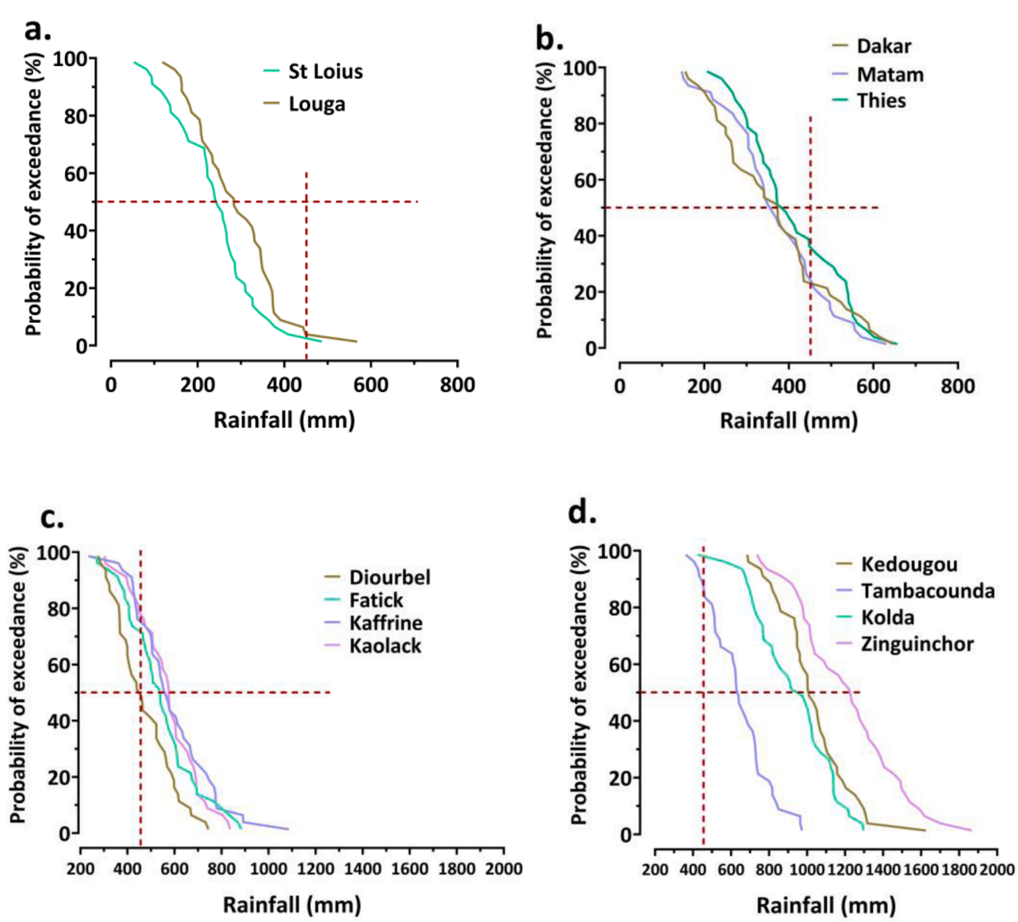

Fig. 2. The seasonal rainfall probability of exceedance charts for the locations in the (a)Sahelian, (b) Sahelian-Soudanian, (c) Soudanian- Sahelian, and (d) Soudanian-Guinean climatic zones from 1981 to 2020.

to Sah and Sah-Sou locations, the locations in the Sou-Sah and Sou-Gui zones receive a seasonal rainfall amount of at least 450 mm more often, i.e., at least in 7 out of 10 rainy seasons. The probability of getting at least 450 mm per season ranges between 70% and 95% at the stations in the Sou-Sah and Sou-Gui locations (Fig. 2c and 2 d) and is higher than at the Sah and Sah-Sou locations whose probabilities range between 15% and 40%. The former locations have a lower risk of crop failure, especially in the seasons in which rainfall is fairly distributed.

3.1.2. Annual and seasonal rainfall trends

The Mann-Kendall test results regarding the long-term trends of both amount and number of rainy days in the annual and seasonal trend diagrams are presented in Tables S2, S3, and Fig. S1 (in supplementary materials). We found significant increasing trends in annual rainfall amounts in all locations except for Tambacounda, Kedougou, and Thies locations which showed insignificant increasing trends. Also, we found significant increasing trends in the amount of seasonal rainfall in all locations except in Dakar, St. Louis, and Thies (Table S2). At the same time, however, we also found insignificant increasing trends in the annual number of rainy days in all the locations except Dakar, Kaolack, Louga, and Matam (Table S3). The number of rainy days in the rainy seasons in the study locations also showed insignificant increasing trends in many locations except in Kaolack, Louga, Matam, and Tambacounda. Compared to increasing trends in the amount of rainfall the trends in the number of rainy days imply an increase in daily rainfall intensity in the study area.

3.2. The onset of the West African Monsoon in the study area

We computed the onset dates from 1981 to 2020 as days of the year (Almorox and Martí, 2022) in each location according to the four definitions used in this study i.e., Raman's(D_1), modified Sivakumar's (D_2), and Yamada's (D_3), and Liebmann's (D_4) onset definitions. We then calculated the average onset date in each location according to all four definitions and compared them. Our analysis showed a statistically significant difference ($F(3,48) = 8.31$, $p = 0.001$) between the onset dates defined by the four definitions. A Tukey comparison test revealed statistically significant differences only between the onset dates in D_1 – D_2 ($p = 0.0035$), D_1 – D_3 ($p = 0.0002$), and D_1 - D_4 ($p = 0.0022$) (Table S4 and S5 in supplementary materials).

Fig. 3 represents the differences observed on the onset dates as defined by the four definitions in the study locations. In Saint Louis and Dakar, the onset dates were between 16th July and 15th August according to the modified Sivakumar's, Yamada's, and Liebmann's definitions while in the same locations, the onset dates were after 15th August according to Raman's definition. All the locations in the Sou- Sah climate zone had their onset dates between 16th June to 15th July according to the modified Sivakumar's, Yamada's, and Liebmann'sdefinition except Diourbel which had onset dates between 16th July to 15th August according to the modified Sivakumar's definition similar to all locations in the same climatic zone according to Raman's definition.

According to all four onset date definitions, in the wettest locations (Sou-Gui climate zone) the monsoon onset is between the 15th of and May to 15th of July. The average onset dates according to Yamada's definitions in all Sou-Gui locations were between 15th May and 15th June. However, only two locations—Kedougou and Kolda—and three locations— Kedougou, Kolda, and Tambacounda— had onset dates between 15th May and 15th June according to Liebmann's and the modified Sivakumar onset definitions respectively. Other locations in this zone had onset dates between 16th June to 15th July.

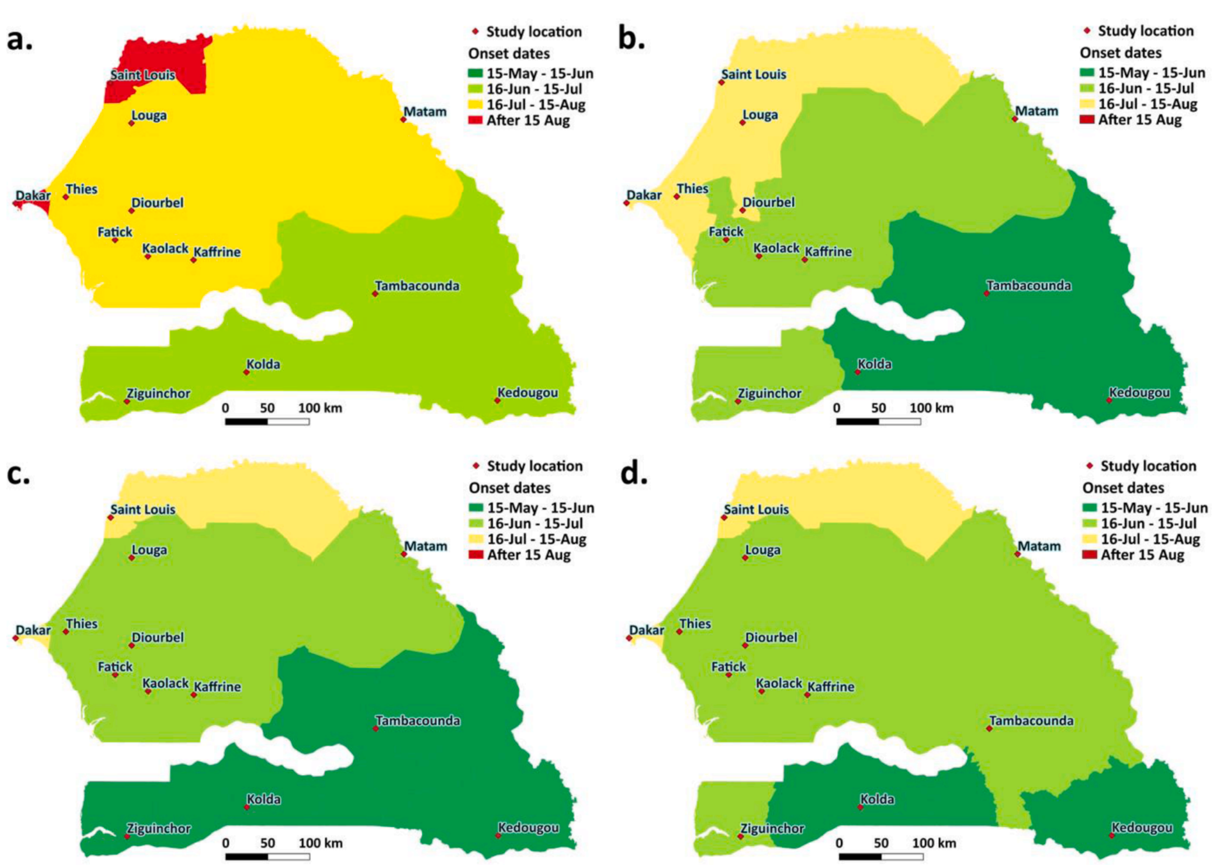

Fig. 3. Onset dates as defined by the four definitions i.e. (a) Raman's(D_1), (b) modified Sivakumar's (D_2), (c) Yamada's (D_3), and (d) Liebmann's (D_4) per definition in the study locations from 1981 to 2020.

3.3. Climatic risk assessment related to onset definitions

3.3.1. Timing of the monsoon onset according to the four definitions

The timing of the onset of the monsoon is a crucial aspect of planning and managing agricultural activities. We examined how timely are the onset dates according to the four definitions relative to a meteorological reference date i.e. 1st June. 1st June is a suitable reference date to characterize a delay or early onset in the study locations because the same is associated with the dynamics of several events such as the movement and position of the intertropical convergence zone (ITCZ), sea surface temperatures evolution, land surface boundary conditions (albedo or moisture level), atmospheric humidity, location and intensity of Hadley-type and Walker-type vertical circulations which all affect significantly the onset and intensity of the West African monsoon (M. V. K. Sivakumar, 1992). We used the five-year return period to assess the risks related to the distribution of the onset dates defined by the four definitions due to their relevance and applicability in hydrological risk analysis (Read and Vogel, 2015).

We represented the 20th percentile of the onset dates distributions according to the four definitions in the locations under the study area in Table S8 (in supplementary materials). Our analysis showed that Raman's definition delayed the monsoon onset at least two to four weeks after 1st June while the other three definitions delayed the onset one to two weeks after 1st June except for the modified Sivakumar definition which had onset dates 5 and 13 days earlier before 1st June in Tambacounda and Kedougou respectively. On average in 4 out of 5 seasons (80%), the onset dates occur after the 30th of July, 3rd of July, 27th of June, and 2nd of July according to Raman's, modified Sivakumar's, Yamada's, and Liebmann's definitions respectively in the Sah and Sah-Sou locations. In the Sou-Sah locations, the seasons had a high probability (80%) of starting after 16th July, 23rd June, 14th June, and 19th June according to Raman's, modified Sivakumar's, Yamada's, and Liebmann's definitions respectively. Moreover, in the Sou-Gui locations, the chance of the season onset after 19th June, 28th May, 03rd June, and 6th June according to Raman's, modified Sivakumar's, Yamada's, and Liebmann's definitions respectively is high (80%).

3.3.2. Mid-season dry spells of n length after the onset of the monsoon

To characterize the occurrence of dry spells related to the onset dates in the mid-season (i.e., during peak crop growth and water requirements during flowering and early ripening), we computed the probabilities of getting a dry spell exceeding 20 or 25 days within a 50-day window that occurred one and a half months after the onset. 50 days window was chosen based on the relationship between the maize phenological stages and their daily water requirement (Fig. S4). Within this window—50 days and one and a half months after sowing—the maize plant is within critical stages of water requirement which implies that moisture deficit at these stages will lead to high yield loss. The results are summarized in Table 1.

On average, the probabilities of getting dry spells of more than 20 and 25 days were higher in D_1 compared to D_2, D_3, and D_4 in the mid-season i.e., 45 to 95 days after onset in both the Sah, Sah-Sou, and Sou-Sah locations. In the Sah climate zone, Saint Louis had the lowest probability (< 20%) of getting a dry spell of more than 20 days after the D_2 onset dates. Moreover, the probabilities of getting a dry spell of more than 25 days in the mid-season were lowest (<20%) in Louga and Saint Loius after the D_2 and D_4 onset dates respectively. In Matam and Thies the D_2, D_3, and D_4 onset dates were followed by the lowest probabilities (<20%) of getting a dry spell of at least 20 days in the mid-season. However, the probability of getting a dry spell of more than 20 days in Thies followed by D_2 onset dates was slightly high (23%). The rest of the onset dates were followed by higher probabilities (> 20%) of getting dry spells of at least 20 days.

The onset dates according to D_2, D_3, and D_4 had $a < 20\%$ probability of getting a dry spell of more than 20 or 25 days in all locations in the Sou-Sah climate zone. However, D_1 onset dates were followed by higher probabilities (ranging from 28 – 65%) of getting a dry spell of more than 20 days in the same climate zone in the mid-season. The Sou-Gui locations had very low probabilities of getting dry spells of at least 20 days—ranging from 0 to 10%—among all the four onset date definitions used in the present study (Table 1).

3.3.3. Mid-season rainfall distribution after the onset of the monsoon

The higher probabilities of having prolonged dry spells in at least half of the mid-season imply a significant reduction in both the number of rain days and the amount of rainfall. Such conditions in a rain-fed system create severe water deficit during critical growth periods which reduce both yield quantity and grain quality.

Our analyses showed the variation in the mid-season (45 days after onset) rainfall distribution among the locations according to the four onset definitions used in this study. Fig. S3 shows the mid-season rainfall distributions in the study locations according to the four onset definitions. In the Sahelian, the amounts of rainfall in the mid-season calculated with D_1 onset dates were very low—on average less than 120 mm indicated by D_1 boxplots (Fig. S3A in supplementary materials) whose upper quartile was less than 120 mm. However, in the same region, the rainfall amounts in the mid-season computed with the D_4 onset dates were a bit higher—ranging from 120 mm to 145 mm on average—followed by those computed with the D_3 and D_2 onset dates. In the Sah-Sou, Sou- Sah, and Sou-Gui locations the rainfall amount computed with D_3 onset dates was higher followed by those computed with D_4, D_2, and D_1 (Fig. S3).

Table 1
The probabilities (%) of occurrence of a dry spell of length greater than 20 and 25 days in 50 days window starting one and a half months after onset according to the four definitions (Raman's(D_1), modified Sivakumar's(D_2), Yamada's(D_3), and Liebmann's (D_4)) in the study locations from 1981 to 2020.

Zone	Location	Probabilities of the dry spell							
		D_1		D_2		D_3		D_4	
		>20	>25	>20	>25	>20	>25	>20	>25
Sahelian	Louga	88	80	38	28	30	23	33	13
	St. Louis	93	88	13	13	43	23	40	23
Sahelian-Soudanian	Dakar	85	78	40	33	28	23	38	28
	Matam	70	63	13	13	10	5	10	3
	Thies	55	45	23	15	5	3	3	3
Soudanian- Sahelian	Diourbel	65	58	15	13	5	5	5	5
	Fatick	53	48	13	10	5	0	3	0
	Kaffrine	45	38	8	5	3	3	3	3
	Kaolack	43	28	8	3	3	0	0	0
Soudanian-Guinean	Kedougou	0	0	0	0	0	0	0	0
	Kolda	5	0	0	0	0	0	0	0
	Tambacounda	10	8	0	0	0	0	0	0
	Zinguinchor	0	0	0	0	0	0	0	0

The difference in the average rainfall amounts among the four definitions was statistically significant ($p < 0.05$, Table S6A, S6A, and S6A) in supplementary materials) in the Sah, Sah-Sou, and Sou-Sah climate zones while the same was statistically insignificant ($p = 0.9039$, Table S6D) in the Sou-Gui climate zone. A Tukey pairwise comparison (Table S7) of means showed that the mean differences were statistically significant among $D_1 - D_2$, $D_1 - D_3$, and $D_1 - D_4$ onset dates only.

3.4. Simulated maize yields

We examined the impact of the sowing dates generated according to the four onset definitions as well as for different soil conditions (i.e., in particular, plant available water capacity (PAWC) and soil organic carbon), and climatic conditions on the simulated maize yields for the 40 years, 1981–2020. We fitted a general linear model to evaluate the significance of the interaction of the maize yield determinants i.e. PAWC, sowing dates, and soil organic carbon in the four climatic zones used in the present study. Our analyses revealed significant interactions between the effect of PAWC, soil organic carbon, and the sowing dates on simulated maize yields in the four climatic zones ($p < 0.05$ (Table S9, S10, S11, and S12 in supplementary materials)). The aforementioned interactions implied that the relationship between the sowing dates according to the four definitions used in the present study and the simulated maize yields also depends on soil conditions such as the level of PAWC and soil organic carbon.

We further examined the main effects of each of the determinants of the simulated yields. Fig. 4 shows the main effects plots of the simulated maize yield determinants, i.e., PAWC, sowing dates, and soil organic carbon. The sowing dates and the level of PAWC were associated with the highest yields in the Sahelian climatic zone while the effect of the soil organic carbon levels on simulated yields was statistically insignificant.

The sowing dates generated according to Liebmann's onset definition in the Sahelian climatic zone had the highest average yields among all onset definitions. Moreover, a high level of PAWC resulted in higher yields than medium and low-level PAWC (Fig. 4a). In the Sah-Sou and Sou- Sah climatic zones, both sowing dates, the level of PAWC, and soil organic carbon significantly impacted the simulated maize yields. The highest level of PAWC and a high amount of organic carbon (OC as a proxy for soil fertility) were associated with the highest yields in the aforementioned climatic zones (Fig. 4b and c).

The sowing dates generated according to Liebmann's(D_4) definition were associated with the highest yields followed by those generated by Yamada's(D_3) and modified Sivakumar's(D_2) definitions. Similarly, in the Sou-Gui climatic zone both sowing dates, the level of PAWC, and soil organic carbon had a significant impact on the simulated maize yields. The highest level of PAWC, high OC, and the sowing dates according to Sivakumar's onset definition were associated with the highest yields (Fig. 4d).

We examined how different combinations of soil and climate conditions led to simulated yield variabilities in the study locations. Our analyses revealed the differences in the yields achieved through various combinations of different soil (PAWC and soil organic carbon) and management conditions (sowing dates). Fig. 5 represents the average yields simulated using four different sets of sowing dates under various levels of soil water (PAWC) and soil fertility (organic carbon) in different climatic zones. On average the simulated maize yields were 1.8, 2.0, 2.6, and 2.7 t/ha in the Sah, Sah-Sou, Sou- Sah, and Sou-Gui climatic zones, respectively. The four sets of sowing dates in different PAWC and soil organic levels achieved different amounts of yields of which some of which were above or below the aforementioned averages. The probabilities of getting a below-average yield (1.8 t/ha) given various combinations of PAWC and soil organic carbon levels were higher under sowing dates generated according to D_1 followed by D_3, D_2, and D_4 in the Sah climatic zone while the probabilities of getting below-average—2.0 t/ha, 2.6 t/ha, and 2.7 t/ha in the Sah-Sou, Sou- Sah, and climatic zones respectively—were higher under sowing dates generated according to D_1 followed by D_2, D_3, and D_4. The sowing dates in D_4 under different PAWC and soil organic levels we applied in the present study resulted in higher yields than any other sowing date.

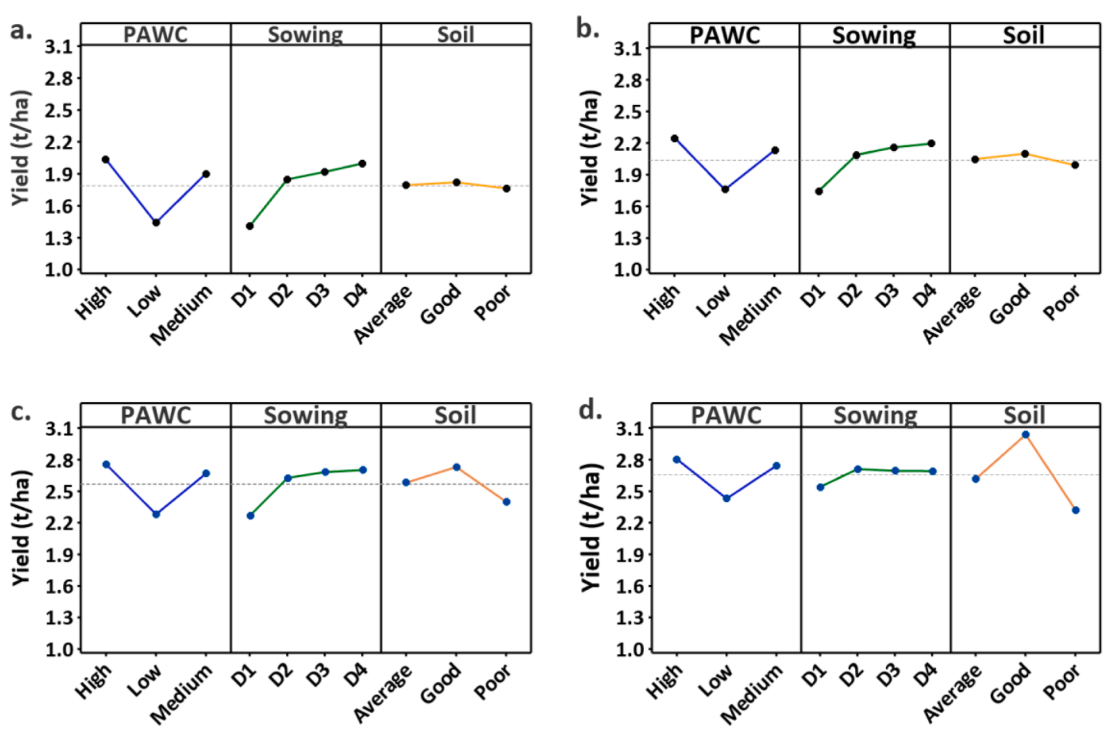

Fig. 4. Main effects plots of the maize yield determinant factors i.e., PAWC, sowing dates, and soil organic carbon in different climatic zones i.e. (a)Sahelian, (b) Sahelian-Soudanian, (c) Soudanian- Sahelian, and (d) Soudanian-Guinean.

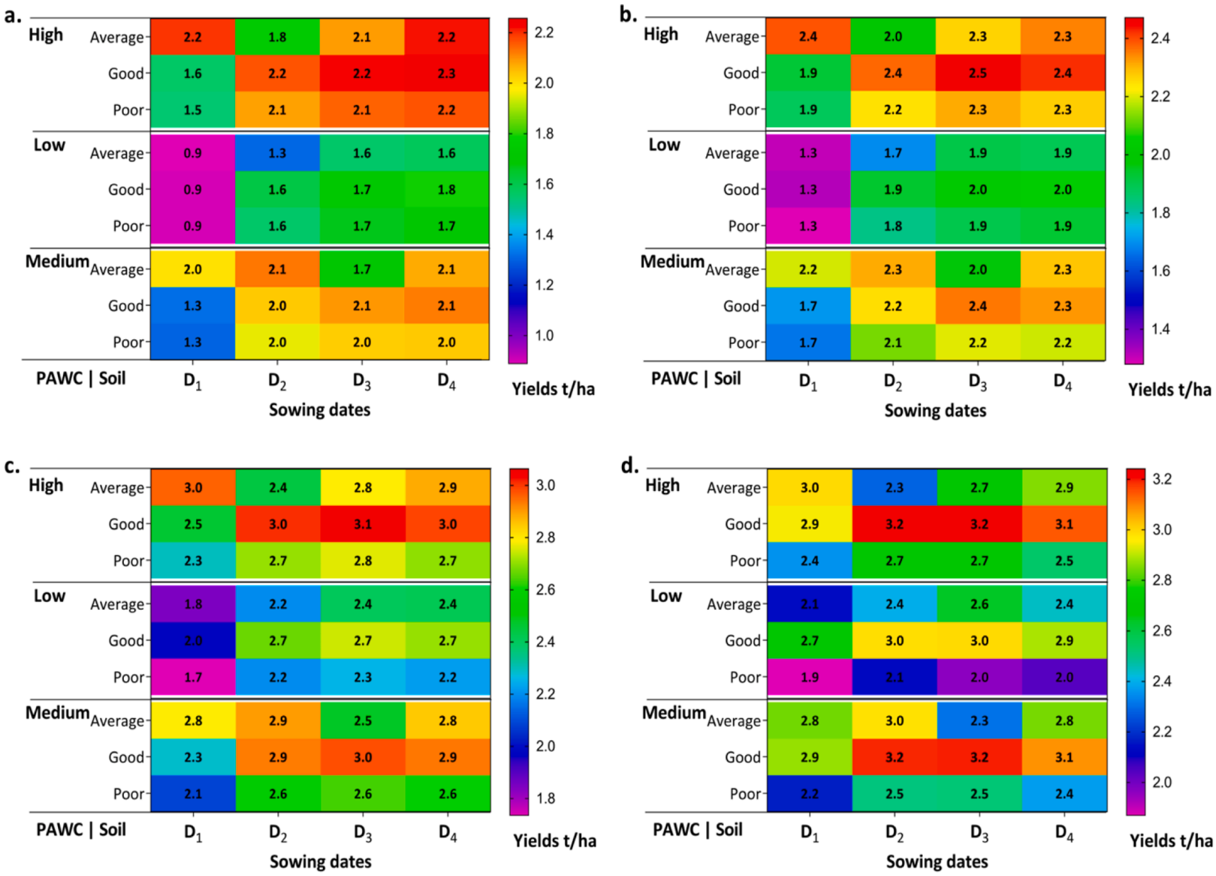

Fig. 5. Average simulated maize yields (t ha^{-1}) for different soil organic carbon levels (average, good, and poor), different levels of PAWC (high, low, and medium), and different sowing dates (i.e. according to onset definitions of Raman's(D_1), Modified Sivakumar's(D_2), Yamada's (D_3), and Liebmann's (D_4)) in main the four different climatic zones i.e. (a) Sahelian, (b) Sahelian-Soudanian, (c) Soudanian- Sahelian, and (d) Soudanian-Guinean.

4. Discussion

We assessed how crop yield variabilities in Senegal relate to the key characteristics of the West African monsoon i.e., intensity and onset of the monsoon, using four different onset definitions. Our analyses confirmed the complex Spatio-temporal variation of rainfall during the wet season (Faty, 2018) among the locations in the study area. Moreover, we found the sowing dates based on the onset definitions used in the present study resulted in significant crop yield variabilities and, thus, suggested an optimal onset date definition that can be used in sowing decisions to mitigate the impact of climate variability in the study area.

4.1. Rainfall trends and variability

Our analyses revealed complex rainfall patterns and an uneven spatial distribution of rainfall among the climatic zones in the study area (Faty, 2018). The locations in the Sah, Sah-Sou, and Sou- Sah zones were found to be drier than the locations in the Sou-Gui zone. Likewise, in that order, they showed higher inter-annual rainfall variability, were characterized by a fewer number of rainy days during the growing season and had a lower probability of getting seasonal rainfall that meets the minimum water requirements of high-water demand crops such as maize. In contrast, the locations in the Sou-Gui climatic zone were wetter than the locations in the other climate zones, had on average higher amount of rainfall and number of rainy days with low inter-annual variability, and a higher probability of getting seasonal rainfall amount that meets the minimum water requirement of most dryland crops (Sarr et al., 2013). The increasing trends in rainfall amount and insignificant increasing trends in the number of rainy days imply a significant increase in the daily rainfall intensity and the frequency of occurrence of extreme events (Ahmed et al., 2021; Nouaceur and Murarescu, 2020; Wilcox et al., 2018).

The observed seasonal rainfall distribution, trends, and variabilities among the study area's climatic zones greatly impact the agricultural production of smallholder farming systems. Such systems are often less resilient to both climatic and socioeconomic shocks than market-oriented commercial larger farms (Córdova et al., 2019; Middendorf et al., 2021). Unfortunately, the current policies and governmental and institutional support measures do not favor the effective implementation of advanced and science-based technologies and practices (Osabohien et al., 2019) that can decrease the negative environmental impacts and increase the resilience of the prevailing agricultural systems. Hence, agricultural activities remain challenging under both, current and future climatic conditions. This is likely to increase food insecurity and hunger and aggravate poverty in the country (Hummel, 2015).

4.2. Factors affecting maize yield and its variability

It has been argued that an optimal onset date of the monsoon should be one characterized by the optimum length of the growing period and followed by fewer occurrences of long dry spells to minimize the risks related to water deficit during the growing period especially the mid-season breaks (Vega et al., 2020). The four onset definitions used in the present study characterized the growing season differently and remarkably affected both the rainfall distribution and the simulated maize yield and its inter-annual variability (Fitzpatrick et al., 2015; Xu et al., 2021).

Late onsets i.e., from late June to August, were frequent (in 4 out of 5 seasons) according to Raman's definition while in other definitions the onset dates before 15th July were frequent (in 4 out of 5 seasons). Moreover, we found the average seasonal rainfall amounts according to Raman's were extremely low and characterized by higher probabilities— greater than 50% on average in all the climatic zones except the Soudanian-Guinean climatic zone— of occurrence of prolonged dry spells of more than 20 or 25 days in the mid-season (one and a half month after onset). In rain-fed systems, such distribution often leads to critical water stresses which significantly lower crop productivity (Jin et al., 2018) as was the case in the maize simulated yields according to Raman's sowing dates which were lower compared to the modified Sivakumar's, Yamada's and Liebmann's sowing dates.

In addition to good management practices such as timely sowing, soil organic carbon and plant available water capacity are important aspects that enhance crop productivity (Ghimire et al., 2017). Similar to other studies (Ghaley et al., 2018; Oelofse et al., 2015) our analyses showed that both soil organic carbon and PAWC had a positive influence on maize yields, however, their influence also depends on the climate and time of sowing. Higher levels of soil organic carbon, PAWC, and Liebmann's sowing dates were associated with an increase in maize yields while the low levels of both soil organic carbon, PAWC, and Raman's sowing dates were associated with low yields. We suggest care should be taken when one base his/her sowing decision relying on Raman's onset dates definition, especially for high-water demand crops such as maize. In a harsh production environment such as the one characterized by the low amount of seasonal rainfall, poor to average fertile soil, and low to medium level of plant available water capacity, Liebmann's onset dates may be regarded as a potential adaptation measure to cope with climate variability and change in the study area. We found that Liebmann's onset definition is the most suitable among the definitions - especially in the aforementioned environment – because when following the related onset dates, rainfall becomes persistent in occurrence, duration, and intensity (Dunning et al., 2016).

Accurate prediction of onset dates using the methods assessed in the present study and communicating this kind of information to smallholder farmers will help them in strategic planning such as the selection of crop varieties, input, labor, and land preparation, which all add value to their production and minimize climate risks (Rao et al., 2017). Despite the usefulness of the methods evaluated in this study, several limitations must be highlighted. First, the four definitions necessitate the use of quantitative data, such as daily rainfall data, which is scarce and of poor quality in Sub-Saharan African countries. Second, the use of these definitions to guide strategic decisions is constrained by the type and accuracy of seasonal climate forecasts provided by the relevant meteorological department, which are frequently qualitative (probabilistic). Third, the examined onset definitions cannot account for or predict extreme rainfall events, which frequently follow dry periods in the middle of the season, which also limits crop production. A separate method is required to analyze the distribution of extreme rainfall events.

5. Conclusions

Despite several socioeconomic factors that influence sowing decisions among the farmers in the Sahel, monsoon onset dates have a considerable influence on sowing decisions and impact the performance of Sahelian rainfed systems. We have shown the need for and importance of defining the monsoon onset accurately, and of taking the specific information needs of agronomic activities into account to improve crop yields – and thereby, food security and livelihoods of smallholder farmers. We have shown that monsoon onset definitions available in literature differ significantly and that careful examination is crucial before using a particular definition for informing decision-making. We highly recommend increasing the access of farmers to climate information services and the availability of long-term monsoon onset forecasts to help the farming activities in their region. Moreover, we encourage agronomic practices that improve the soil organic carbon level of the soil and other soil qualities/properties that have a positive effect on crop productivity and yields.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Supplementary materials

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