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Analysis of the Dynamics of the Onset of the Rainy Season in Relation to Crop Productivity in West Africa



David Agoungbome

**ANALYSIS OF THE DYNAMICS OF THE ONSET OF THE
RAINY SEASON IN RELATION TO CROP
PRODUCTIVITY IN WEST AFRICA**

ANALYSIS OF THE DYNAMICS OF THE ONSET OF THE RAINY SEASON IN RELATION TO CROP PRODUCTIVITY IN WEST AFRICA

Dissertation

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Keywords: Onset, False Start, Safe Sowing Windows, West Africa, AquaCrop
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*To Degnon Joseph, my late father,
for his unwavering dedication to my education.
Forever grateful.*

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SUMMARY

Recent shifts in climate conditions have disrupted rainfall patterns in the Sudanian region of West Africa, causing local farmers to struggle with adjusting their farming strategies (Biasutti, 2019; Gbangou et al., 2019; Tzachor et al., 2023). This has led to the phenomenon known as the 'false onset' or 'false start' of the rainy season, which is characterized by erratic rain events at the beginning of the season, followed by intermittent dry spells of various lengths (Laux et al., 2008; Silungwe et al., 2019). Given that farming in the region is predominantly rainfed, and seasonal rainfall patterns largely guide planting decisions, traditional sowing strategies need to be reconsidered given these changing conditions. This research aims, therefore, to analyze the impact of changes in the dynamics of rainfall patterns in West Africa on crop yield for rainfed agriculture. Specifically, it will examine the effect of several different sowing strategies on crop yield using a crop simulation model.

First, it provides an overview of local farming practices in the Sudanian region of West Africa, alongside farmers' perspectives on climate change and the adaptive measures they use. The findings are based on interviews with local farmers in the region and discussions with research institutes and regional agencies involved in climate change, adaptation, and agricultural water management. Two main approaches were used during the interviews: semi-structured individual interviews based on a questionnaire and group discussions. The investigation revealed that farmers are acutely aware of the changing climate and its negative impact on crop production. The traditional practice of sowing after the first two rainfalls has become increasingly unreliable under current climate conditions. There is a consensus among farmers that the rainfall total has decreased, the duration of the season is shortening, and there is a high frequency of dry spells throughout the rainy season. Additionally, there is a notable lack of climate-based services to support farmers' decision-making processes. Consequently, smallholder farmers expressed a strong interest in receiving not only weather forecasts but also climate risk information, which is crucial for making agriculture in the region more resilient to climate change.

Chapter 3 examines various sowing strategies used in the rainfed farming system of West Africa, where intermittent dry spells during the rainy season exacerbate challenges and affect crop yield response. In the context of a changing climate, we hypothesize that the traditional focus on the onset of the season to start sowing leads to crop losses in years of high rainfall intermittency. Using AquaCrop, an FAO crop model, we simulate the crop response to varying water availability to sowing dates ranging from the 1st of May to the 30th of November at 20 locations in WA. The crop we focus on is maize (*Zea mays* L.). The analysis revealed that sowing directly after the first rains carries a higher risk of yield loss due to insufficient buildup of soil water storage to overcome dry spells. Based on three years of data per station on average between 2016 and 2020, various sowing strategies were evaluated. We identified safe sowing windows across the Sudanian

region that secure optimal yield in 97% of all cases. We find that delaying sowing to mid-June (savanna and western part of the region) and to July (semi-arid region) ensures optimal yields. Of the three commonly applied local onset approaches covered in our evaluation, only the local onset LO10mm, defined as four consecutive days with 10 mm/day, achieves a similar yield result. The advantage of the safe sowing window approach is that it is easily accessible for smallholder farmers, who in many cases do not have access to local rainfall information.

Chapter 4 focuses on identifying sowing strategies that minimize yield losses at the regional level. Climate variability poses great challenges to farmers in the region who are heavily dependent on rainfall for farming. Hence, we investigate three sowing strategies available in the Sudanian region of West Africa (WA) to assess their ability to ensure crop yields for smallholder farmers under a changing climate. AquaCrop-GIS, the GIS version of the FAO crop model, is used to simulate the yield response of maize (*Zea mays* L.) to varying sowing dates (1st of May to 30th of November) throughout the rainy season across WA. Based on an average of 38 years of data per grid cell from the Global Precipitation Climatology Centre (GPCC), we identify safe sowing windows across the Sudanian region that secure at least 90% of maximal yield. The analysis revealed that the current sowing strategies, based on minimum thresholds for rainfall accumulated over a period, widely applied in the region, carry a higher risk of yield failure than the safe sowing window strategy, especially at the beginning of the rainy season. It also appears that delaying sowing for a month to mid-June in the central region (east of Lon 8.5°W), and to early August in the semi-arid areas is a safe strategy for smallholder farmers that ensures optimal yields. A long-term comparison between the periods 1982–1991 and 1992–2019 reveals earlier sowing dates for both LO10 mm and LO20 mm, indicating a shift towards a wetter regime relative to the reference period. In contrast, the safe sowing window strategy shows later sowing dates, underscoring the need for caution due to erratic early-season rainfall and variability beyond the control period defined by local sowing practices. The precipitation-based strategies hold a higher risk of yield failure compared to the safe sowing window strategy, which is more accessible to smallholder farmers and better suited to the current climate conditions.

The key findings of this dissertation contribute to regional efforts in building a climate-resilient agricultural system by equipping smallholder farmers with simple yet effective sowing strategies. The research recommendations offer practical, easily implementable solutions for smallholder farmers across West Africa. Given the dynamic nature of rainfall distribution and the uncertainty in future climate projections for West Africa, it is essential to strengthen regional initiatives that improve access to rainfall data and climate services. These efforts will equip farmers with the tools and knowledge needed to make informed decisions. As our understanding of rainfall patterns evolves, updating these recommendations will be crucial to mitigating the negative effects of dry spells and enhancing crop productivity across the region. Additionally, regional efforts should prioritize enhancing and expanding climate and weather monitoring infrastructure to improve our understanding of the region's complex weather systems at a finer scale. This will enable more precise modeling of the intricate weather-crop-soil interactions and provide localized information to smallholder farmers. Leveraging crop simulation models will facilitate the exploration of both current and future scenarios, helping to identify

the most efficient farming practices. This will ultimately improve water use efficiency and contribute to closing the food security gap.

RÉSUMÉ

"Les récents changements observés dans les conditions climatiques ont perturbé les régimes de précipitations dans la région soudanienne de l'Afrique de l'Ouest, obligeant les agriculteurs locaux à réajuster leurs stratégies agricoles (BIASUTTI, 2019; GBANGOU et al., 2019; TZACHOR et al., 2023). Cela a conduit au phénomène connu sous le nom de "faux démarrage" de la saison des pluies, caractérisé par des événements pluvieux irréguliers au début de la saison, suivis de périodes sèches intermittentes de diverses durées (LAUX et al., 2008; SILUNGWE et al., 2019). Étant donné que l'agriculture dans la région est principalement pluviale, et que les régimes saisonniers de précipitations déterminent en grande partie les décisions de plantation, les stratégies traditionnelles de semis doivent être réévaluées face à ces nouvelles conditions climatiques. Cette recherche vise donc à analyser l'impact des changements dans la dynamique des régimes de précipitations en Afrique de l'Ouest sur le rendement des cultures pour l'agriculture pluviale. Plus précisément, elle examinera l'effet de plusieurs stratégies de semis différentes sur le rendement des cultures à l'aide d'un modèle de simulation agricoles.

Dans un premier temps, un aperçu des pratiques agricoles locales dans la région soudanienne de l'Afrique de l'Ouest est proposé, ainsi que les perspectives des agriculteurs sur le changement climatique et les mesures d'adaptation qu'ils utilisent. Les résultats présentés ici sont donc basés sur des entretiens avec des agriculteurs locaux dans la région et des discussions avec des instituts de recherche et des agences régionales qui œuvrent dans le changement et l'adaptation climatique, ainsi que la maîtrise de l'eau en agriculture. Deux approches principales ont été utilisées lors des entretiens : des entretiens individuels semi-structurés basés sur un questionnaire et des discussions de groupe. L'enquête a révélé que les agriculteurs sont pleinement conscients du changement climatique et de ses impacts négatifs sur la production agricole. Ainsi, la pratique traditionnelle consistant à semer après les deux premières pluies devient de plus en plus incertaine dans les conditions climatiques actuelles. De plus, un consensus s'est dégagé parmi les agriculteurs selon lequel la quantité de précipitations a diminué, la durée de la saison s'est raccourcie, et la fréquence des périodes sèches au cours de la saison des pluies est élevée. En outre, il existe un manque notable de services climatiques pour soutenir les processus décisionnels des agriculteurs. Par conséquent, ces petits paysans ont exprimé un vif intérêt pour recevoir non seulement des prévisions météorologiques, mais aussi des informations sur les risques climatiques, ce qui est crucial pour rendre l'agriculture dans la région plus résiliente au changement climatique."

Le chapitre 3 examine diverses stratégies de semis utilisées dans le système agricole pluvial de l'Afrique de l'Ouest, qui est en proie aux périodes sèches intermittentes pendant la saison des pluies, ce qui affectent les rendements des cultures. Dans le contexte d'un climat en évolution, nous posons l'hypothèse que l'accent traditionnel mis sur le début de la saison pour commencer les semis entraîne des pertes de récoltes les années où les intermittences des pluies sont élevées. En utilisant AquaCrop, un modèle agri-

code de la FAO, nous simulons la réponse des cultures à la disponibilité de l'eau pour des dates de semis allant du 1er mai au 30 novembre dans 20 localités d'Afrique de l'Ouest. La culture étudiée est le maïs (*Zea mays* L.). L'analyse a révélé que semer directement après les premières pluies comporte un risque plus élevé de perte de rendement en raison d'un manque de stockage d'eau dans le sol suffisant pour surmonter les périodes sèches. Basée sur des données couvrant en moyenne trois ans par station entre 2016 et 2020, plusieurs stratégies de semis ont été évaluées. Nous avons ainsi identifié des fenêtres de semis sûres à travers la région soudanienne qui garantissent un rendement optimal dans 97 % des cas. Nous avons constaté que retarder les semis jusqu'à la mi-juin (dans la savane et l'ouest de la région) et jusqu'en juillet (dans la région semi-aride) assure des rendements optimaux. Parmi les trois approches locales couramment utilisées pour définir le début de la saison, seule la méthode locale LO10mm, qui définit le début de la saison comme quatre jours consécutifs avec 10 mm de pluie par jour, obtient un résultat de rendement similaire. L'avantage de la stratégie de la fenêtre de semis sûre est qu'elle est facilement accessible aux petits paysans, qui, dans de nombreux cas, n'ont pas accès à des informations locales sur les précipitations.

Le chapitre 4 se concentre sur l'identification de stratégies de semis minimisant les pertes de rendement à l'échelle régionale. La variabilité climatique pose de grands défis aux agriculteurs de la région, fortement dépendants des précipitations pour la culture agricole. Ainsi, nous investiguons trois stratégies de semis disponibles dans la région soudanienne de l'Afrique de l'Ouest (WA) pour évaluer leur capacité à assurer de bons rendements agricoles pour les petits paysans dans un climat changeant. AquaCrop-GIS, la version SIG du modèle de culture de la FAO, est utilisé pour simuler la réponse du rendement du maïs (*Zea mays* L.) à des dates de semis variables (du 1er mai au 30 novembre) tout au long de la saison des pluies dans toute l'Afrique de l'Ouest. Sur la base d'une moyenne de 38 ans de données par de grille provenant du Global Precipitation Climatology Centre (GPCC), nous avons identifié des fenêtres de semis sûres à travers la région soudanienne qui garantissent au moins 90 % du rendement maximal. L'analyse a révélé que les stratégies de semis actuelles, basées sur des seuils minimaux de précipitations cumulées sur une période donnée, largement appliquées dans la région, comportent un risque plus élevé d'échec des récoltes que la stratégie de la fenêtre de semis sûre, en particulier au début de la saison des pluies. Il apparaît également que retarder les semis d'un mois, jusqu'à la mi-juin dans la région centrale (à l'est de la longitude Lon 8,5°W), et jusqu'au début d'août dans les zones semi-arides, constitue une stratégie sûre pour les petits paysans, garantissant des rendements optimaux. Une analyse sur le long terme entre les périodes 1982–1991 et 1992–2019 révèle des dates de semis précoces pour les stratégies LO10 mm et LO20 mm, indiquant un passage vers un régime plus humide par rapport à la période de référence. En revanche, la stratégie de la fenêtre de semis sûre montre des dates de semis plus tardives, soulignant la nécessité de prendre des précautions face à la variabilité des précipitations en début de saison et à la variabilité au-delà de la période de contrôle définie par les pratiques de semis locales. Les stratégies basées sur des seuils minimaux de précipitations cumulées sur une période donnée comportent un risque plus élevé d'échec des récoltes par rapport à la stratégie de la fenêtre de semis sûre, qui est elle plus accessible aux petits paysans et mieux adaptée aux conditions climatiques actuelles.

Les conclusions clés de cette thèse contribuent aux efforts régionaux visant à construire un système agricole résilient au climat en dotant les petits paysans de stratégies de semis simples mais efficaces. Les recommandations de la recherche offrent des solutions pratiques et facilement applicables pour les petits paysans à travers l'Afrique de l'Ouest. Étant donné la nature dynamique de la distribution des précipitations et l'incertitude des projections climatiques futures pour la région de l'Afrique de l'Ouest, il est essentiel de renforcer les initiatives régionales visant à améliorer l'accès aux données sur les précipitations et aux services climatiques. Ces efforts permettront de doter les agriculteurs des outils et des connaissances nécessaires pour prendre des décisions éclairées. À mesure que notre compréhension des régimes de précipitations évolue, il sera crucial de mettre à jour ces recommandations pour atténuer les effets négatifs des périodes sèches et améliorer la productivité des cultures dans toute la région. De plus, les efforts régionaux devraient se concentrer aussi sur le renforcement et l'expansion des infrastructures de surveillance climatique et météorologique afin d'approfondir notre compréhension des systèmes météorologiques complexes de la région à une échelle plus fine. Cela permettra de modéliser avec plus de précision les interactions complexes entre le climat, les cultures et les sols, et de fournir des informations localisées aux petits paysans. En exploitant les modèles de simulation agricoles, il sera possible d'explorer à la fois les scénarios actuels et futurs, aidant ainsi à identifier les pratiques agricoles les plus efficaces. Cela améliorera l'efficacité de l'utilisation de l'eau et contribuera à réduire le déficit de sécurité alimentaire."

1

INTRODUCTION

In order to increase our material resources, we have, as a major priority, to raise significantly agricultural productivity. This is a pre-condition for our industrial growth

...

There must be a transformation of our subsistence farms into commodity producing farms, so that they may provide enough food for our steadily rising population, give raw materials to feed secondary industries, and cash crops to help pay for our necessary imports.

Kwame Nkrumah, *Africa must unite* (1963), p.121

1.1. THE CHALLENGE OF THE FALSE START OF THE GROWING SEASON IN WEST AFRICA

In the farming systems of West Africa, more than 90% of farmers depend on seasonal rainfall. Rainfall patterns guide the timing of sowing or planting and the selection of crop types (Adjei-Gyapong and Asiamah, 2002; Ismaila et al., 2010). The success or failure of a growing season strongly rests on identifying the right planting date for a given crop. Traditional and indigenous practices have been successful across the region. Farmers observed several triggers ranging from migrant birds, the green leaves that appear on the Baobab tree, the maturing, ready-to-be-harvested fruits on the Dawadawa tree, to the change in the color and shape of clouds (Codjoe et al., 2014; Gbangou et al., 2020; Gyampoh et al., 2009). However, these triggers are becoming less effective and have failed more frequently under the present-day climate conditions, leading more often to crop failure (Roncoli et al., 2002).

One of the problems farmers have been reporting is the so-called "false start" of the rainy season (Sultan and Gaetani, 2016). The false start or "false onset" is characterized by erratic rain events at the beginning of the season followed by intermittent dry spells of various lengths (Laux et al., 2008; Silungwe et al., 2019). The issue of the false start of the rainy season in the savanna region has challenged not only local knowledge but also recommendations for suitable sowing dates. In the last years, agro-climatologists have proposed two onset approaches to address the challenge of false starts in WA which can be broadly classified based on the scale on which they are applied, i.e. i) the regional onset approach based on atmospheric dynamics, and ii) the local onset approach using meteorological observations at the field scale. The regional approach is associated with the northward migration of the Intertropical Convergence Zone (ITCZ) also referred to as the tropical rain belt from the Guinea Coast (latitude 5°N) toward the Sudan/Sahel area (latitude 10°N) (Fitzpatrick et al., 2015). This sudden northward shift of the ITCZ to the Sudanian region marks the beginning of deep convective activities (intense rains) and is considered the onset of the West African Monsoon season (Fontaine and Louvet, 2006; Fontaine et al., 2008; Gazeaux et al., 2011; Gu and Adler, 2004; Hagos and Cook, 2007; Sultan and Janicot, 2003). The local-scale approach onset definitions rely on a given empirical threshold of accumulated rainfall totals over a control period at specific locations. They provide a more specific onset measurement for local stakeholders and end-users (Ati et al., 2002; Marteau et al., 2009; Omotosho et al., 2000; Vellinga et al., 2012; Yamada et al., 2013). These empirical thresholds aim to ensure minimum necessary soil moisture for the crop during the initial developmental stage. For instance, LO10mm and LO20mm are the two major local-scale approaches commonly used in the region. The local onset LO20mm defines the onset of the rainy season as one or two consecutive rainy days accumulating at least 20 mm with no 7-day dry spell occurring during the next 30 days counted from the onset (Marteau et al., 2009). The local onset LO10mm, termed agro-nomical onset, accounts for both rainfall and evapotranspiration and defines the start of the growing season as an average of four consecutive rainy days exceeding 10 mm daily (Gbangou et al., 2019).

The practical applicability of the onset approaches at the field scale faces several challenges. The regional onset approach gives onset dates for a wide band of longitudes

(Marteau et al., 2009), without accounting for regional spatial variabilities. Moreover, the regional onset approach does not consider rains before the shift of the ITCZ, the latter being itself a more fluid concept and open to interpretation and modification (Fitzpatrick et al., 2015). The local onset approaches on the other hand require the monitoring of rainfall during the control period before making a decision. This may lead to planting rather late (Ati et al., 2002). Furthermore, as suggested in the pioneering studies that led to most of the local definitions (Sivakumar, 1992), the choice to focus on dry spells from emergence to panicle initiation assumes that dry spells during the flowering stages of cereal crops are less impactful in the semi-arid zone of WA. However, Sultan et al. (2005) showed in a study on millet in Niamey (Niger) that the distribution of dry spells even after the control period is crucial for crop development. Especially long dry spells occurring during the most sensitive stages (i.e. flowering) may cause yield reduction as crops are not able to convert biomass into grain. Hence, it is necessary to assess the effects of dry spells on all crop developmental stages.

Climate variability poses additional threats to the already fragile farming system in West Africa. The global warming observed around the earth and the subsequent changes in the rainfall pattern, challenge any previous strategies in the semi-arid and arid zones that heavily depend on rainfall for farming (Gbangou et al., 2019). The occurrence and frequency of long dry spells at the start, during, and at the end of the rainy season (Froidurot and Diedhiou, 2017; Rockström et al., 2010) continue to challenge local farmers. Climate change exacerbates yield gaps and a low average crop yield, which in most cases remains very low compared to other regions (less than 2 t/ha for maize (Gaetani et al., 2020; Guilpart et al., 2017; Sultan et al., 2014)). Hence, better and innovative management practices are necessary, especially adaptation measures to dry spells and sowing strategies that minimize yield losses for farmers in the region are crucial to securing livelihoods (Gbangou et al., 2020).

1.2. THESIS OUTLINE

Whether regional or local, the approaches to determining the onset of the growing season highlight the primary attention given to the beginning of the rainy season. Although the start of the season is important for crop production, how critical is rainfall variability during the entire growing season? This doctoral research assesses the dynamics of the onset and occurrence of dry spells during the rainy season in the Sudanian region of West Africa. Ultimately, it seeks to identify safe sowing strategies that maximize water availability for crop development, minimize the adverse effects of dry spells, and maximize crop yield. By analyzing crop development and response to different levels of water stress, a better understanding of the weather-crop-soil system will also be established. This will help derive insights and knowledge on the characteristics of the rainy season (onset, duration, and cessation), infer safe sowing windows, and the implication for local farmers to support adaptation measures.

Hence, the methodology of this research focuses on evaluating crop response to varying sowing strategies available in the region. To this end, AquaCrop, a crop simulation model developed by the Food and Agriculture Organization (FAO) is used to understand crop growth from sowing to harvest and the yield produced for a specific sowing date. Throughout the thesis, maize is the main crop on which the analysis focuses. The chap-

ters in this thesis contribute to the overall research objective as follows:

- Chapter 2 examines the local context of farming in West Africa by surveying smallholder farmers in Ghana and Benin, as well as interviews with regional institutions supporting agriculture and adaptation initiatives in the region.
- Chapter 3 aims to identify safe sowing windows for smallholder farmers in West Africa. Where existing approaches focus on sowing early, after the first rains of the season, this chapter analyzes crop response to water availability for a wide range of sowing dates covering the entire rainfall season (May to November).
- Chapter 4 investigates at the region-level three sowing strategies to assess their ability to identify safe sowing windows for smallholder farmers in the Sudanian region of West Africa (WA) in the context of a changing climate. Using 38 years of climate data per grid cell and the crop simulation model AquaCrop-GIS, different scenarios were evaluated to identify safe sowing windows that secure at least 90% of maximal yield.

The concluding chapter 5 synthesizes the main findings of the research, discusses the implications, provides recommendations to farmers and farming associations, and projects an outlook for future research opportunities from this perspective.

2

FARMING PRACTICES IN THE SUDANIAN REGION OF WEST AFRICA IN THE FACE OF CLIMATE CHANGE: A PERSPECTIVE FROM THE GROUND

*Ce ne sont pas les mauvaises herbes qui étouffent le bon grain,
c'est la négligence du cultivateur.*

Proverbe chinois

2.1. INTRODUCTION

Africa's population is growing fast and is projected to double by 2050, requiring that food production must follow a similar increase to meet the growing demand. Even now, the current state of food security and nutrition on the continent is alarming. Nearly 1/3 of Africa's population experiences severe food insecurity and more than half of the population is moderately food insecure (FAO et al., 2019). While the areas of land that are farmed and harvested have more than doubled in Africa since 1995, crop yield productivity remains one of the major challenges of the agricultural sector (Benin, 2016; World Bank, 2009). For instance, in 2017 more than 40 million hectares of farmland in Africa were dedicated to maize cultivation (approx. 20% of the world's total maize farms), but only 7.4% of the total world maize production came from the African continent (FAO, 2019). The causes of this poor productivity in African agriculture are rooted in a lack of climate and weather information available to end-users, a slow technology uptake, and a lack of appropriate financial support for the farmers (Tshabalala et al., 2021). The maize yield gap accounts for more than 80% of the potential yield that could be produced (FAO et al., 2019; Guilpart et al., 2017). In addition to poor crop productivity, many Sub-Saharan African regions are currently subjected to extreme weather events, varying from severe droughts to considerable flooding, with subsequent devastating repercussions on the food security in the region (DEWFORA, 2012; Diffenbaugh and Giorgi, 2012; IPCC, 2012).

West Africa, where more than 90% of crop production is rain-fed and millions of farmers depend on rainfall, is one of the most vulnerable and least monitored regions regarding climate change and rainfall variability (Gizaw and Gan, 2016). Given the high uncertainty of future climate conditions in the region, one must be able to foresee the big challenges that lay ahead for its farmers, such as exposure to damages and crop losses which will lead to food insecurity. Ultimately, if appropriate measures are not put in place to improve productivity, these conditions will result in famine and poverty. This study aims to understand farming practices in the savanna region of West Africa, the adaptation measures that farmers take to cope with changes in the rainfall pattern and the strategies to improve the efficiency and productivity of crop water use.

The study is the initial phase of the research project entitled: "Analysis of the dynamics of the onset of the rainy season in the Sudanian region of West Africa," consisting of the evaluation of different sowing strategies that support efficiently smallholder farmers. Thus, the goal of the interviews was to understand the local context of farming in the region, the local triggers (physical), and factors that play a role in the decision-making process of when to start sowing their crops. Therefore, the field survey was conducted with these three main goals: i) understand the regional farming practices, relating to crop information, soil profile, management practices, application of nutrients and fertilizers, productivity and yield, ii) farmers' perception of climate change, such as the particular perception of climate change including changes in the rainfall pattern, related sowing decisions, and relevant strategies, and iii) ongoing measures to cope with the adverse effects of climate change. This set of information will enable a crop modeling approach to represent the best possible reality on the ground and to design optimal strategies that can function in the regional context.

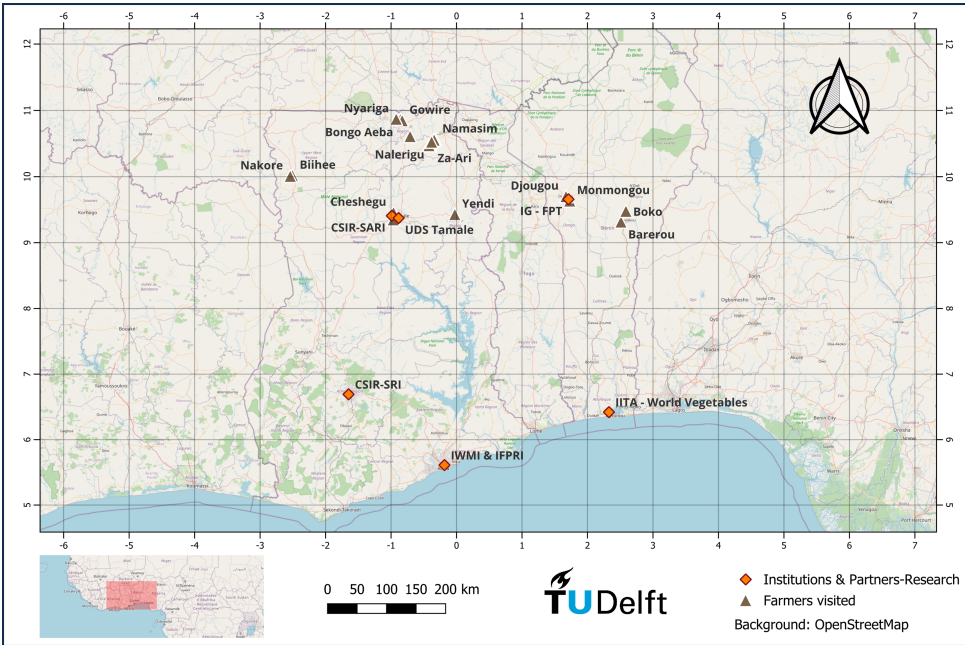


Figure 2.1: Locations of the farmers visited for the interviews, the national and regional institutions supporting agricultural production in West Africa.

2.2. MATERIALS AND METHODS

2.2.1. LOCATIONS VISITED

The field visits spanned a period between 2020 and 2023 and focused on two countries in the Sudanian West African region, namely Benin and Ghana. [Figure 2.1](#) shows the itinerary and the locations visited. We were not able to conduct fieldwork in other countries (Mali, Nigeria, Burkina Faso) due to the political instability and insecurity, but we managed to contact several collaborators for specific information.

2.2.2. METHODOLOGY

The methodology consisted of surveying different stakeholders involved in the agricultural sector in West Africa. For this study, three main categories of stakeholders were consulted: i) farmers and associations of farmers, ii) national agencies supporting agricultural development and smallholder farmers, and iii) regional institutions in charge of the implementation of climate and agricultural programs in a direct or indirect link with farmers. [Table 2.1](#) summarizes the different national agencies and regional institutions involved in this process. The interviews (see appendix) were prepared and conducted in such a way as to enable the interviewees to elaborate on the specific questions/problems. A semi-structured interview was conducted with the participants (one-on-one), and a second interview involved a group discussion. The individual interviews offered the benefit of avoiding group consent and enabling each participant to share

personal experiences.

Table 2.1: Different national agencies and regional institutions visited.

Name of the institution	Location	Topics discussed
International Water Management Institute (IWMI) regional office in West Africa	Accra, Ghana	Overview of climate change effects on crop production as well as measures to help farmers to cope with
International Food Policy Research Institute (IFPRI)	Accra, Ghana	Public initiatives to help farmers cope with climate change and improve crop productivity; policy analysis
Ministry of Food and Agriculture	Accra, Ghana	Agriculture data, governmental support projects
Centre for Climate Change and Sustainability Studies at University of Ghana	Accra, Ghana	Climate trend in West Africa and impacts on crop production,
Soil Research Institute	Kumasi, Ghana	Soil data (soil profile and texture features) of the northern regions
University of Development Studies	Tamale, Ghana	Adaptive measures implemented by farmers
West African Science Service Center on Climate Change and Adaptive Land Use (WASCAL),	Bolgatanga, Ghana	How we can engage with farmers and understand how they choose the moment to start planting
Savanna Agriculture Research Institute (SARI)	Tamale, Ghana	Main challenges faced by farmers in the savanna regions such climate change effects, false start, low crop productivity, decreasing soil fertility and measures to mitigate them

SEMI-STRUCTURED INTERVIEWS WITH SMALLHOLDER FARMERS

In total, 56 farmers and two focus groups were visited in four (Northern, North East, Upper East, and Upper West) out of the five Northern regions of Ghana, and two provinces (Donga and Borgou) in the Northern part of Benin. The farmers were asked a set of seven main questions: 1) the type of agriculture they practiced (rainy and/or dry season farming), what crops they farm, and the size of the farmland; 2) experience in farming and the various changes observed in the climate and the rainfall process since they have started farming until date; 3) the indigenous/local knowledge used to determine the start of the rainy season; 4) the different decisive factors to choose a particular moment of the season to start preparing the farmland and, afterward, the moment to start sowing the seeds; 5) the actions and alternatives in the case of prolonged dry spells/drought; 6) climatological information, or data, that would be useful to the farmers, and the communication channel(s) that would be the most accessible to receive climatological information; and 7) the availability of any crop insurance services in the area and their willingness and financial ability to subscribe to such a service. (See Appendix for the questionnaire).

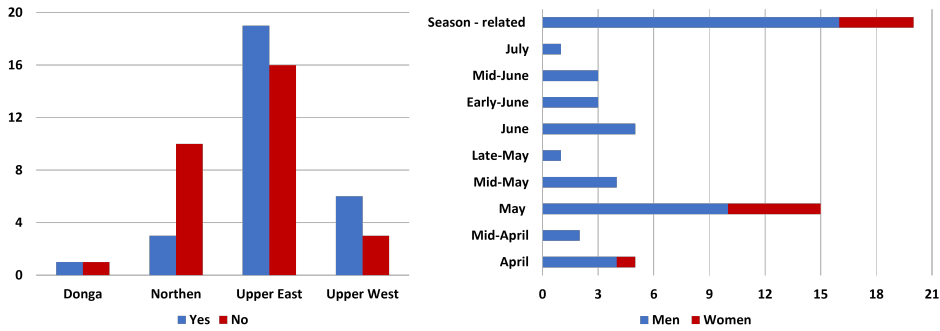


Figure 2.2: (a) Usage of additional water (dry season cropping). (b) Distribution of sowing periods with respect to gender.

GROUP DISCUSSIONS

The group discussions consisted of interviewing individuals within existing associations or cooperatives of farmers in a group setting. The cooperatives usually comprise different types or categories of farmers performing certain agricultural activities, such as labor exchanges, mainly for weeding fields, and working as a group rather than as individuals at each other's farms (Onumah et al., 2007). Such an organization has the advantage of covering an extensive cultivated area by joining forces, sharing experiences and good practices, and minimizing risks through shared benefits and losses schemes. Two groups of farmers participated in the survey and suggested an approach to how group decisions and experiences are aligned with the selection of correct sowing dates.

2.3. RESULTS

2.3.1. STATISTICS OF THE PARTICIPANTS

The distribution of the interviewees is gender unbalanced. Only 17% (10 out of 59) are female. More than half of the farmers (30 participants) do not grow any crops during the dry season, which corresponds exactly to the interviewees (30) who do not have any access to the water sources (shallow water table, river channel, or a dam) in their areas. As there is only one rainy season in the region, most farming activities take place during that period. The size of the farmland ranges from 2 ha to 48 ha, for the biggest exploitation visited, with a mean farm size estimated at 12 ha. The interquartile range varies between 5 ha and 48 ha for the size of farmlands. Due to the decreased interest in farming, the age ranges show farming as an activity for the older generation. The average years of experience of the interviewees is 25 years with an interquartile range between 4 and 50 years.

2.3.2. FARMING PRACTICES

TYPES OF CROPS

In terms of agricultural practices, all farmers in the Sudanian West African region are "rainy season farmers." Only the communities close to a water body, such as a river, a

dam, or a location with a shallow water table, have some form of an irrigation system, traditionally used in addition to the rainy season, or solely in the dry season. In the dry season, farmers mainly grow cash crops such as *tomatoes*, *lettuce*, *chili peppers*, *watermelon*, *onion*, and some leafy vegetables (*Amaranthus*, *okra*, *garden eggs*). The rainy season farming depends heavily on rain and is predominantly not associated with any irrigation system. The main crops are maize, millet, sorghum, groundnut, cowpea, rice, and various beans. Depending on the size of the farm, farmers perform separate cropping, intercropping of different crops, or mixed cropping. In general, farmers grow up to three different crops per season on different plots with many farmers (27%) performing mixed cropping, for example, growing groundnut mixed in with millet.

SOWING STRATEGIES AND DECISIONS

Although there is a somewhat communal general preparation and starting time for sowing in most villages, characterized by common practices such as locking up all the cattle to prevent them from destroying fields, we also notice individual triggers for planting decisions. Considering the objective to optimize productivity, each farmer makes his/her final decision on when to start preparing and planting seeds, depending on the type of crop grown and his/her criteria. After the first rain events, most farmers start clearing the lands to get the fields ready to start sowing, using tractor services to plow the land, while waiting for the next rainfall. The sowing moment is generally on or after the day of heavy rainfall. For most farmers, this will mean that it rains for a whole night or day, or when the soil is moist up to the length of a hand. Other farmers wait for a few more rainfalls before they start sowing, often between two and four rains. In most regions, the farmers who combine groundnut with a crop such as maize, millet, or cowpea, first plant the groundnut, and about two weeks later the other crops will be sown. Some farmers choose a particular moment in the season to start sowing (such as a calendar date) solely based on their experience, no matter what weather has happened before. Among others, we categorize farmers who start planting their crops either from mid to late May, early June, mid to late June, and early July when considering maize, a drought-sensitive crop.

CROP YIELD AND PRODUCTIVITY

Crop productivity was the main focus of the investigation. However, the majority of farmers in Sudanian West Africa, especially smallholder farmers, do not evaluate their production with conventional units (ex: kg/ha). Production is usually expressed in the number of bags per cultivated field. And since there is some approximation in the cultivated area and there is no standard for the bags used (which vary from one farmer to another as well as subject to change in size with time), the estimation has not been collected. Records at district/regional levels, or estimations from field experimentation estimate actual yield for smallholder farmers between 0.5 t/ha to 1.9 t/ha. A couple of educated farmers confirmed these values, while a farmer using improved seeds could harvest up to 3 t/ha in the area of Djougou (Benin).

2.3.3. PLANTING DECISIONS AND TRIGGERS

To determine when the rainy season is approaching several indicators are used, following indigenous knowledge. The first indicator is the Harmattan, a very hot and dusty



Figure 2.3: Triggers that the farmers use to estimate the sowing moments (a) Dawadawa tree in Nareligu, and (b) a shea-nut tree in Pusiga.

wind, occurring from December and January up to March, preceding the rainy season. The end of this period is characterized by very hot and sweaty moments during the day, and this is a signal that the rainy season is approaching. Most farmers also recognize the arrival of the rainy season by the green leaves that appear on the Baobab tree, the shea nuts appearing on the shea nut tree, and the maturing, ready-to-be-harvested fruits on the Dawadawa tree. Other farmers mentioned the change in the direction of the wind that will bring clouds moving eastwards, the change in the color and the form of the clouds, or the arrival of migrant birds. Farmers perceive all these phenomena as indicators to start preparing their farmland. However, to start sowing, they mainly follow a certain number of rains or a particular rain event. In this current context of climate change and with the advancement of science, farmers consider indigenous knowledge as rather rudimentary and not very reliable. Several farmers also said that these indicators are becoming less reliable because of natural rhythms changing at different rates.

2.3.4. PERCEPTION OF CLIMATE CHANGE

The general overview of the different answers shows that farmers perceive climate change as a reduction of the total amount of seasonal rainfall, the shortening of the length of the rainy season, and also as the occasional occurrence of heavy rains which can devastate total crop production. Even though various changes in the rainfall pattern have been reported, only 50% of the respondents observed a shift in the onset and/or cessation of the rainy season. As a result, 30% the farmers have actively taken measures by shifting their timing of land preparation and/or sowing of the crops.

Farmers declared that in past decades, the onset of the rainy season was early in March, followed by regular, continuous, and consistent rains. They acknowledged that dry spells did occur in those times as well, but would never last more than two weeks without a single rain event. Moreover, the rainy season could often last until November. They added that nowadays, the onset of the rainy season has shifted to late May, followed by a period with intermittent droughts, and consistent rains usually settle in in June and last until September. The rainy season would finish with some rain events

in October. Only 14% of the respondents could relate or link the present changes in rainfall distribution, the shift of the start of the rainy season to June, or later moments to the effect of climate change and have undergone adaptation strategies to cope with the situation. Compared to the dry spells in the past, as experienced by the interviewed farmers, today's dry spells are longer and can last from four weeks up to two months in the worst-case scenario. A particular emphasis was put on the year 2019, with a severe four-week-long dry spell in August.

2.3.5. OCCURRENCE OF DRY SPELLS AND COPING MECHANISMS

The question of the occurrence of dry spells and how to handle prolonged dry spells, was by all farmers perceived as having no control over the season; prayers to God for a good season would send rains at the needed time. Here, we can also categorize farmers into two groups: (i) the first category comprises farmers who leave everything “up in the air” to decide and wait and pray in expectation for the rains, which may come or may not come; they mostly are at the higher risk, (ii) the second category of farmers take quick actions, to either replant the same crop when the plants fail to grow well or die, or implement mixed cropping, with a short duration crop able to withstand drought, such as millet or cowpea or plow the failed land and sow a short duration crop that can withstand drought, such as millet or cowpea. This choice generally depends on the moment and timing in the rainy season, and on how much time they expect to have until the end of the rainy season. Most farmers do not use irrigation in a drought situation to provide additional water to the rainy season crops. The only exception we encountered in this particular situation was a group of farmers along the White Volta River, near Bolgatanga. They generally farm dry-season crops in the lowlands, next to the river, and wet-season crops in the uplands. However, they also plant some wet-season crops, such as maize in the lowlands, to be able to irrigate them with the river water and not lose everything in case of a mid-season drought.

2.3.6. CROP INSURANCE AND WEATHER SERVICES

Because of their high dependence on rain, all farmers said they would find it tremendously useful to get more information about rainfall. Particularly they would welcome information on the rainfall distribution during the season such as the onset and the end of the season, the occurrence and the duration of dry spells during the growing season, and the appropriate crops to grow. The preferred communication channels to receive such information would be radio, TV, mobile phone, and extension agents. One aspect they highlighted was that due to their general illiteracy of English, this information should be communicated in their local dialects. The Ghana Meteorology Service does communicate climate and weather information to several communities. However, they recognized that the information was not always accurate and relevant, and has led to failure.

Finally, concerning the possibility of a crop insurance service, we found a general lack of knowledge or a lack of trust about insurance services, and in several cases, farmers were even unaware of insurance services for farmers. Only in two communities (Nareligu, in the North East, and Yendi, in the Northern region of Ghana) a few farmers had heard of, or subscribed, to crop insurance services in the past. The insurance insti-

tution in Nareligu was called World Cover (<https://esa-worldcover.org/en>), an insurance service that covers maize, groundnut, soybean, and rice in case of drought crises. The price was 20 Ghana Cedis (4 USD) for 1 hectare (in our research period, 2020-23). The problem with World Cover as a service provider was the fact that they just collected the subscription fees from the farmers but did not compensate them after a failed harvest. In Yendi, a farmer's name was listed to be compensated, but the service provider never came back to provide the contracted insurance coverage. Therefore, for the communities where no one has ever heard of crop insurance, we used the health insurance scheme to explain what crop insurance is. Once we explained what crop insurance was and how it works, there was a general interest in this kind of service, mainly motivated by the big losses that farmers have experienced in recent years.

2.4. DISCUSSION

2.4.1. DIFFICULTIES ENCOUNTERED DURING THE STUDY

Although the local authorities expressed a willingness to support food production in the region, data scarcity is a recurrent challenge both at high and low administration levels. Since the majority of the smallholder farmers have little or no education, data is often not recorded by individual farmers. Thus, the information on various aspects of farming (annual yield, occurrence, and duration of dry spells, sowing days, etc.) comes from the back of their mind, which may have some memory lapse or gap. Other information, such as farm size, productivity, and worst-case scenario events that they have experienced, are all subjected to a similar uncertainty due to the lack of an administrative system.

The savannah region of West Africa hosts a high diversity of local communities spread out over a large territory and across many local dialects, making an investigation of various farming strategies and a survey regarding farm size and productivity more challenging. Discussions and meetings with farmers were therefore in most cases not feasible, requiring the help of an interpreter/translator with a good knowledge of the subject. Some terms such as climate change, adaptation, and productivity were difficult to translate in both directions/senses, sometimes leading to misunderstandings.

2.4.2. NEED TO IMPROVE FARMING PRACTICES

According to Guilpart et al. (2017), the yield gap in Sub-Saharan Africa (SSA) is the highest in the world (for example for maize, it is 1.3 t/ha in the USA compared to 11 t/ha in SSA). There is an urgency to close this gap through different means, thus requiring several aspects of the farming system to change and adapt. The following strategies stimulating change and adaptations are suggested, such as the improvement of soil properties, the use of climate-resilient seeds to cope with current climate conditions, a technology uptake, i.e. small irrigation systems, the establishment of financial incentives and mechanisms to support farmers' losses (Tshabalala et al., 2021). Recent highlights from SSA estimated that with improved (genetically engineered) seeds, farmers can increase maize yield by up to 3.0 t/ha in Nigeria (FAO, 2019) and 5.9 t/ha in South Africa (Sihlobo, 2020) showing that half of this gap can be reduced just through improved seeds. The increasing duration of dry spells poses a threat to productivity that drought-resistant varieties can mitigate. In such an approach, the use of improved seeds combined with resilience

strategies must be fostered. On the other hand, farm management and adaptation to current conditions are highly needed to optimize the agricultural process in this region.

2

2.4.3. NEED FOR CLIMATE-ORIENTED DECISION TOOLS FOR FARMERS

The exposure of smallholder farmers in the Savanna region of West Africa to climate change highlights the urgency for a paradigm change. Especially, knowing that these farmers contribute to the majority of food production in the region where we seek to reduce food insecurity and vulnerability to climate. In this case, particular attention is needed to increase real-time monitoring in order to apply quick risk assessment and to have early warning systems in place. The need for climate services to support good farming practices has initiated multiple projects on this part of the continent, among others, the AMMA-CATCH initiative, the WASCAL project, and the TAHMO project. Supporting the farmers implies not only assessing climate risks but also providing information to end-users (local farmers). Even though a lot of studies have been conducted, the consecutive step of making the outcomes available and accessible to end-users is usually missing. Different means could be explored, such as GSM operators for voice messages and institutionalizing platforms to share knowledge in order to build a common resilience, as well as to enable information sharing through cooperatives of farmers. Most importantly, equipping role model farmers has the potential to facilitate the dissemination of adaptation measures and coping mechanisms.

2.5. CONCLUSION

In conclusion, this investigation shows the vulnerability of the smallholder farmers in the Sudanian region of West Africa and the lack of climate-based services to support farmers' decision-making processes. Several factors have played a role in selecting a sowing date in the past, but these factors are less reliable under the current climate conditions. Sowing occurs mainly after the first two rainfalls and the application of fertilisers is quasi non-existent. Reverting the exposure of the smallholder farmers implies supporting them not only with weather services but also with climate risk information and identifying the appropriate means to make it accessible to end-users.

2.6. APPENDIX A: QUESTIONNAIRE FOR THE INTERVIEW WITH STAKEHOLDERS IN THE SUDANIAN REGION OF WEST AFRICA

2.6.1. OBSERVED CHANGES IN THE RAINFALL PATTERNS

- Variability of the amounts of rain (annually, during the crop season)?
- What is the frequency of dry spells within the rainy seasons?
- Sowing date of maize, sorghum, and millet? Is the sowing date fixed or variable every year? and what determines the changes.
- What are the effects of climate change on the rainy season and impacts on crop production?

2.6.2. CROP INFORMATION

- Characteristics of cultivars (time to emergence, max CC, max rooting depth, start of senescence, maturity, flowering, harvest index, etc.).
- What is the canopy cover of the farmed land?
- What is Maximum rooting?

2.6.3. SOIL INFORMATION

- What is the type of soil of the region?
- Composition of the soil in terms of % sand, clay, and organic matters?
- What are erosion impacts on land properties?

2.6.4. MANAGEMENT PRACTICES

- How well irrigation is practiced?
- Is mulch applied and to which extent?
- Plant density per hectare?

2.6.5. APPLICATIONS OF NUTRIENTS AND FERTILIZERS

- To which extent nutrients and fertilizers are applied in crop production?
- What are the constraints noticed?
- What are the alternatives to the NPK? Local Production or Natural Fertilizer?

2.6.6. PRODUCTION AND YIELD

- What is the range of the yield of the main crop (maize, sorghum, millet)?
- What are the main impacts of climate change on productivity (quantity, quality of the crop, diseases, pests)?
- What are the measures to improve crop productivity?

2.6.7. CLIMATE CHANGE

- What are the perceptible changes in Temperature, ET_o, and Rains

2.6.8. QUESTIONS TO REGIONAL AND RESEARCH INSTITUTIONS

- What are the variations observed for the past 50 years in the rains/rainy season?
- Is there any shift in the rainfall isohyets?
- What are the causes for the low productivity of crop production?
- What causes massive failures in some years?
- What are the years with such failure in production?
- Extremes events (droughts and floods) in the region
- False starts? and the impacts?
- What are the adaptation measures established (past, present, and ongoing)?
- Development of improved type of seeds and what are the characteristics?
- What is the crop (Maize, Sorghum, Millet) factor for the region?

2.6.9. QUESTIONS TO EXTENSIONS AGENCIES

- Database on historical food price variation or statistics in each year?
- Does the food prices vary and what are the parameters that determine the variation?
- Who and how the data on the prices are collected?

2.7. APPENDIX B: QUESTIONS WITH MULTIPLE ANSWERS**2.7.1. OBSERVED CHANGES IN THE RAINFALL PATTERNS**

- Variability of the amounts of rain (annually, during the crop season)?

More rains	...	No changes	...	Less rains	...	No idea	...
------------	-----	------------	-----	------------	-----	---------	-----

- How many days of rain? /year /rainy season
- What is the frequency of dry spells within the rainy seasons?

More frequent	...	No changes	...	Less frequent	...	No idea	...
---------------	-----	------------	-----	---------------	-----	---------	-----

- How long can a dry spell last on average during the rainy season? /season, for how many times? /season
- Sowing date of maize, sorghum and millet ? Is the sowing date fixed or variable every year?

Fixed	...	Variable	...
-------	-----	----------	-----

- What determines the changes, and how the choice is made?
- Do they apply the inter-cropping method, and what are the combinations?
- What are the effects of climate change on the rainy season and impacts on crop production?

2.7.2. CROP INFORMATION

- What is the type of seed that you use?
- Where do you obtain the seeds from?
- How long does it take to harvest?
- When does the flowering start?
- What is the canopy cover of the farmed land?
- What is the Maximum depth of the root?cm

2.7.3. SOIL INFORMATION

- What is the type of soil of the region?
- Composition of the soil in terms of % sand, clay, and organic matters?

Sand	...%	Clay	...%	Organic matter	...%
------	------	------	------	----------------	------

- What are erosion impacts on land properties ?.....

2.7.4. MANAGEMENT PRACTICES

- How well irrigation is practiced?

Everyday		During dry spells		No irrigation		Other answer (OA)	
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- OA.....
- Is mulching applied and to which extent ?

Yes	...	No	...	To what extent	...%
-----	-----	----	-----	----------------	------

- Plant density per hectare?

Plant to plant space	...cm	In row space	...cm
----------------------	-------	--------------	-------

2.7.5. APPLICATIONS OF NUTRIENTS AND FERTILIZERS

- To which extent nutrients and fertilizers are applied in crop production?
- What are the constraints noticed ??
- What are the alternatives to the NPK? Local Production or Natural Fertilizer?

2.7.6. PRODUCTION AND YIELD

- What is the range of the yield of the main crop (maize, sorghum, millet)?

Maize	...t/ha	Sorghum	... t/ha	Millet	... t/ha
-------	---------	---------	----------	--------	----------

- What are the main impacts of climate change on productivity (quantity, quality of the crop, diseases, pests) ??? (-/-/+ /++)

Quantity	...	Quality	...	Diseases	...	Weeds/Pests	...
----------	-----	---------	-----	----------	-----	-------------	-----

- What are the measures to improve crop productivity ??

2.7.7. CLIMATE CHANGE

- What are the perceptible changes in Temperature, ETo, and Rains? (-/-/+ /++)

Temperature	...	Rains	...	Drought	...	Floods	...
-------------	-----	-------	-----	---------	-----	--------	-----

Notations:

– very low

- low

+ high

++ very high

3

OPTIMAL SOWING WINDOWS UNDER RAINFALL VARIABILITY IN RAINFED AGRICULTURE IN WEST AFRICA

*Climate change is exacerbating the adverse impacts of water stress in rainfed agriculture. This paper seeks to identify safe sowing windows for smallholder farmers in the Sudanian region of West Africa (WA). We hypothesize that the traditional focus on the onset of the season to start sowing leads to crop losses in years of high rainfall intermittency. AquaCrop, an FAO crop model, is used to simulate the yield response of maize (*Zea mays* L.) to sowing dates ranging from the 1st of May to the 30th of November at 20 locations in WA. We find that sowing directly after the first rains carries a higher risk of water stress, hampering crop development due to insufficient buildup of soil water storage to overcome dry spells. Based on three years of data per station on average, we identify safe sowing windows across the Sudanian region that secure optimal yield in 97% of all cases. We find that delaying sowing to mid-June (savanna and western part of the region) and to July (semi-arid region) ensures optimal yields. Of the three commonly applied local onset approaches covered in our evaluation, only LO10mm (10 mm/day on four consecutive days) achieves a similar yield result. The advantage of the safe window approach is that it is accessible for smallholders, who in many cases do not have access to local rainfall information.*

This chapter is based on: **Agoungbome, S.M.D.**; ten Veldhuis, M.-C.; van de Giesen, N. *Optimal Sowing Windows under Rainfall Variability in Rainfed Agriculture in West Africa*. Agronomy 2023, 13, 167. (Agoungbome et al., 2023).

3.1. INTRODUCTION

Food production is under increasing pressure worldwide to feed the ever-growing population (Berners-Lee et al., 2018). At the same time, in 2021, a quarter of the population in Sub-Saharan Africa was facing moderate to severe food insecurity (FAO et al., 2022). The situation is especially precarious under rain-fed agriculture, where there are no mitigating measures that can be taken to cope with climate extremes. Reliance on rain-fed agriculture in West Africa (WA) is particularly problematic, as rainfall patterns are highly variable on decadal and inter-annual time scales (Gbangou et al., 2019). To help farmers deal with this rainfall uncertainty, agro-meteorological indices have been introduced to support farmers in making crop decisions. However, the occurrence of long dry spells (7 to 15 days) at the start and end of the rainy season (Froidurot and Diedhiou, 2017; Rockström et al., 2010) continues to have negative effects on crop yields, which in most cases remain below 2 t/ha for maize (Gaetani et al., 2020; Guilpart et al., 2017; Sultan et al., 2014). Hence, better management practices are necessary, especially adaptation to dry spells at the start of the season, which is a predominant factor in crop yield losses (Gbangou et al., 2020).

The unpredictability of the onset of the rainy season has led to the so-called phenomenon of the “false start” or “false onset” characterized by erratic rain events at the beginning of the season, followed by intermittent dry spells of various lengths (Laux et al., 2008; Silungwe et al., 2019). In the last decades, agro-climatologists have proposed two onset approaches to address the challenge of false starts in WA. While the approach based on atmospheric dynamics or regional onset focuses on the migration of the Inter-tropical Convergence Zone (ITCZ) from latitude 5°N to 10°N (Fontaine et al., 2008; Gazeaux et al., 2011), the local onset approach focuses on empirical thresholds of accumulated rainfall totals over a period of time (control period) (Ati et al., 2002; Marteau et al., 2009; Yamada et al., 2013). A case study in Niger for the years 1968–1990 highlights the strong link between dry spells at late crop stages and yield failure (Sultan et al., 2005). Thus, while the start of the season is crucial, rainfall variability throughout the growing season needs attention.

Assessing the rainfall pattern can elucidate critical periods and stress-sensitive stages that could potentially hinder crop development. Such an analysis helps in identifying safe sowing windows and can support farmers in making informed decisions and improving yields (Gbangou et al., 2019). In addition to the study by Gbangou et al. (2019), we include different locations and associated water stress levels and identify safe planting windows. Moreover, the development of crop insurance products, such as germination insurance, can greatly profit from better insights into optimal sowing dates.

In this study, we aim to identify robust sowing windows within the rainy season that secure crop yield under rainfall variations. We use a water-driven crop growth model, AquaCrop v6.1, run with meteorological observations from 20 stations across the Sudanian agro-climatological region to study yield response to rainfall variability for a wide range of sowing dates. We evaluate existing rainfall-based definitions of local onset use in the region to start sowing in order to assess whether they fall within the safe sowing window. The outcomes can help farmers prevent untimely sowing decisions and optimize rainwater use to secure crop yields.

3.2. DATA DESCRIPTION

3.2.1. STUDY AREA

The study area is the Sudanian agro-climatological region of WA. The majority of food crops in WA are grown under rainfed and labor-intensive conditions (Ismaila et al., 2010). The main crops grown are maize (*Zea mays* L.), sorghum (*Sorghum bicolor*), Pearl millet (*Pennisetum glaucum*), and beans (*Phaseolus vulgaris* L.). The climatology of the region is characterized by an unimodal rainfall season that runs from April/May through October, following a northward latitudinal gradient associated with the ITCZ (Aryee et al., 2018). Mean daily temperature during the rainy season varies from 26 °C in the south to 30 °C in the northern part of the region. Annual rainfall ranges from 438 mm to 1265 mm from the north to the south of the Sudanian region (Lebel and Ali, 2009).

3.2.2. DATA SOURCES

Meteorological observations from 20 stations from the network of the Trans-African Hydro-Meteorological Observatory (TAHMO, accessed on 22/06/2021) were used in this study. The stations were selected to represent the range of climate conditions in the study area. Only stations with at least 3 years of continuous data (data gaps of not more than 10 days) were selected for the analysis. The stations are distributed across the Sudanian region (see Figure 3.1) and cover six countries: Benin, Burkina Faso, Ghana, Mali, Nigeria, and Togo. The TAHMO stations provide observations of rainfall, temperature, atmospheric pressure, and relative humidity at a 5-min resolution (van de Giesen et al., 2014a). Table 3.1 provides an overview of the coordinates, mean annual rainfall, and evaporation of the 20 meteorological stations.

Soil profile information was extracted from the Africa Soil Profiles Database, Version 1.2 (AfSP v1.2), compiled by ISRIC—World Soil Information (World Data Center for Soils). We validated the soil profile data using the Soil Atlas of Africa dataset (SAA) at the scale of 1:3 M, derived among others from the Harmonized World Soil Database and the FAO-UNESCO Soil map of the World (Jones et al., 2013). For locations where the soil profile was not available, the dominant WRB reference soil group of the location was extracted from the SAA map, and the closest station having the same soil group and properties was considered for the analysis. Soil texture was used as input into the Soil Water Characteristics module of SPAW (Soil Plant Atmosphere Water), a hydraulic properties calculator, to estimate saturated hydraulic conductivity (K_{SAT}) and water holding capacity of the soil, which are required parameters to run AquaCrop simulations (ars.usda.gov; (Saxton and Rawls, 2006)).

Interviews and discussions with 64 farmers in the northern regions of Benin and Ghana during field trips enabled us to define the management practices (limited/no use of fertilizer, no irrigation) as well as the current practice with respect to sowing time.

3.2.3. SEASONAL VARIABILITY OF RAINFALL AND EVAPORATION IN THE STUDY REGION

The set of stations covers a period of 3 years on average between 2016 and 2020, for a total of 64 years of data analyzed for all the stations together. Average annual rainfall varies between 500 mm/year and 1100 mm/year, reflecting the spatial variability of rain-

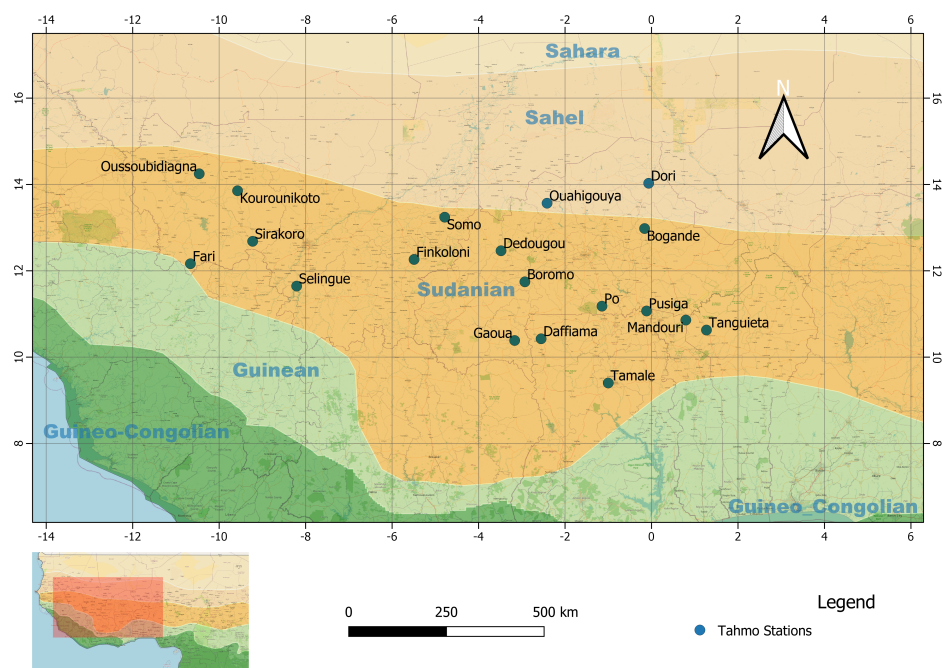


Figure 3.1: Agroclimatological regions in West Africa and the locations of the 20 TAHMO stations across the Sudanian region.

fall with latitude in the Sudanian region of WA (Lebel and Ali, 2009). Most of the rain falls between the months of June and September (80% and 91% on average for the savanna and the semi-arid zones, respectively). Reference evapotranspiration (Eref based on de Bruin and Lablans (1998)) is nearly twice the annual precipitation, yet during the rainy season, Eref nearly equals this amount of rainfall.

Figure 3.2 presents the average seasonal rainfall sufficiency (cumulative difference between daily precipitation and evapotranspiration, for the months of May to October) for each of the 20 stations, sorted by latitude (low to high). At most stations (13 out of 20), seasonal rainfall can meet evaporative demand (Sufficiency ≥ 0). In total, the dataset contains seven severe dry years out of the 64 years with annual rainfall about/below half of the average annual rainfall. There are also ten years with lower annual rainfall than the long-term mean.

3.2.4. DRY SPELLS DURING THE GROWING SEASON

With all stations used in this study, we have a total of 64 years, allowing for more general summary statistics. On average, each station experienced 30 (std = 8) and 7 (std = 3.5) dry spells of 3 and 7 consecutive dry days per rainy season, respectively (Figure 3.2). We analyzed the frequency of dry spells exceeding 7 and 10 days within the 30 days following a reference date. Reference dates are defined as the first day of each of the three dekads of

Table 3.1: TAHMO stations, names and IDs, coordinates, mean annual rainfall ($\bar{P}_{an}$) and reference evapotranspiration ($\bar{E}_{ref}$ based on Makkink (de Bruin and Lablans, 1998)) and period of data availability.

ID	Stations	Coordinates	Country	Mean $\bar{P}_{an}$ (mm/yr)	Mean $\bar{E}_{ref}$ (mm/yr)	Period
Bog	Bogande	12.98° N ; 0.16° W	Burkina Faso	489	1253	2017–2019
Bor	Boromo	11.74° N ; 2.93° W	Burkina Faso	1013	1252	2018–2020
Daf	Daffiama	10.42° N ; 2.55° W	Ghana	796	1287	2018–2020
Ded	Dedougou	12.46° N ; 3.48° W	Burkina Faso	920	1205	2017–2020
Dor	Dori	14.03° N ; 0.07° W	Burkina Faso	438	1349	2017–2020
Far	Fari	12.16° N ; 10.67° W	Mali	984	1127	2018–2020
Fin	Finkoloni	12.26° N ; 5.49° W	Mali	971	1499	2017, 2019–2020
Gao	Gaoua	10.39° N ; 3.17° W	Burkina Faso	1102	1280	2017–2020
Kou	Kourounikoto	13.85° N ; 9.58° W	Mali	989	1276	2018–2020
Man	Mandouri	10.86° N ; 0.79° W	Togo	613	1050	2018–2020
Oua	Ouahigouya	13.57° N ; 2.42° W	Burkina Faso	984	1282	2017–2020
Ous	Oussoubidiagna	14.25° N ; 10.46° W	Mali	619	1185	2018–2020
Po	Po	11.18° N ; 1.4° W	Burkina Faso	1265	1160	2017–2020
Pus	Pusiga	11.07° N ; 0.11° W	Ghana	1227	1155	2018–2020
Sel	Selingue	11.65° N ; 8.21° W	Mali	478.4	1220.2	2018–2020
Sir	Sirakoro	12.68° N ; 9.23° W	Mali	987	1110	2018–2020
Som	Somo	13.24° N ; 4.78° W	Mali	487	1532	2017, 2019–2020
Tam	Tamale	9.50° N ; 1.00° W	Ghana	589	1205	2019–2020
Tan	Tanguieta	10.63° N ; 1.27° E	Benin	981	1071	2017–2020
Uni	Unimaid	11.81° N ; 13.21° E	Nigeria	504	1315	2016–2017, 2020

each month of the rainy season. The term dekad here refers to days 1–10, 11–20, and 21–30/31 of each month, as defined by (Sivakumar, 1992). For each 30-day period, the maximum length of dry spells was determined. This length was compared to the threshold values (7 and 10) to calculate the frequency of 30-day periods in which it was exceeded for the length of the 3-year dataset.

Figure 3.3 shows the dekadal occurrence of dry spells in the growing season for four selected locations representative of wet and well-distributed (Gaoua and Dedougou) and dry or unevenly distributed (Oussoubidiagna and Dori) rainy seasons. At well-watered stations such as Gaoua, the risk of long dry spells (≥ 7 days and ≥ 10 days) is quite low after mid-May (<25%), whereas at drier stations (Oussoubidiagna and Dori) the risk is greater than 70% until mid-June. The rain season is shorter at these stations, with dry spell occurrence increasing steeply after mid-July. Three out of four stations experience a period of increased risk of dry spells in the middle of the season (mid-June to early July).

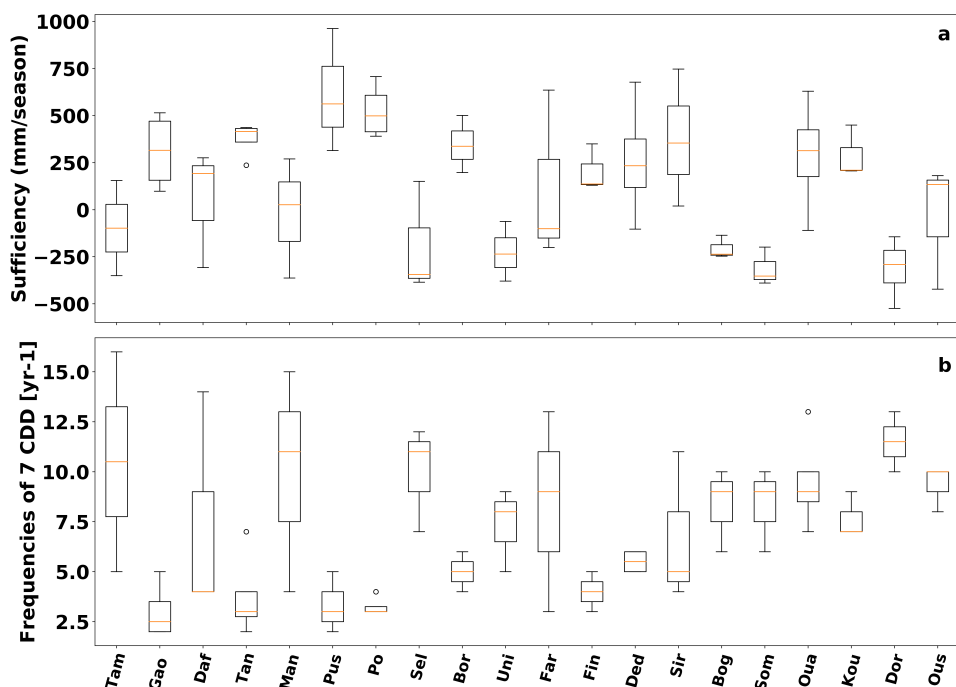


Figure 3.2: (a) Average rainfall sufficiency in the growing season (from May to October), computed as the difference between daily precipitation and evapotranspiration. Evaporation computed following Makkink (de Bruin and Lablans, 1998). (b) Frequency of 7-day consecutive dry days (CDD), mean, and variability over the study period. Stations are ordered by increasing latitude from left to right.

3.3. METHODS

3.3.1. DEFINITIONS OF THE ONSET OF THE RAINY SEASON FOR AGRICULTURE

In this study, we focus on the local or precipitation threshold-based onset, which is deemed most relevant for smallholder farmers in WA with lower levels of education (Nyadzi, 2020). The alternative regional onset approach requires information at a level not generally accessible to small-scale farmers (Fitzpatrick et al., 2015). We consider three local onset definitions based on the literature and local practices in the WA region. The first, LO20mm hereafter, defines the onset as one or two consecutive rainy days accumulating at least 20 mm with no 7-day dry spell occurring during the next 30 days counted from the onset (Marteau et al., 2009). This approach prioritizes sufficient water availability; however, it requires a long control period (30 days) until farmers can start to plant. The second approach, FP20mm, which is mostly practiced by smallholder farmers in the region, is based on one or two consecutive days of rain with a total of about 20 mm. This should ensure sufficient soil humidity to sustain seed germination (Huho, 2011; Marteau et al., 2011; Silungwe et al., 2019). The third local onset approach, termed agronomical

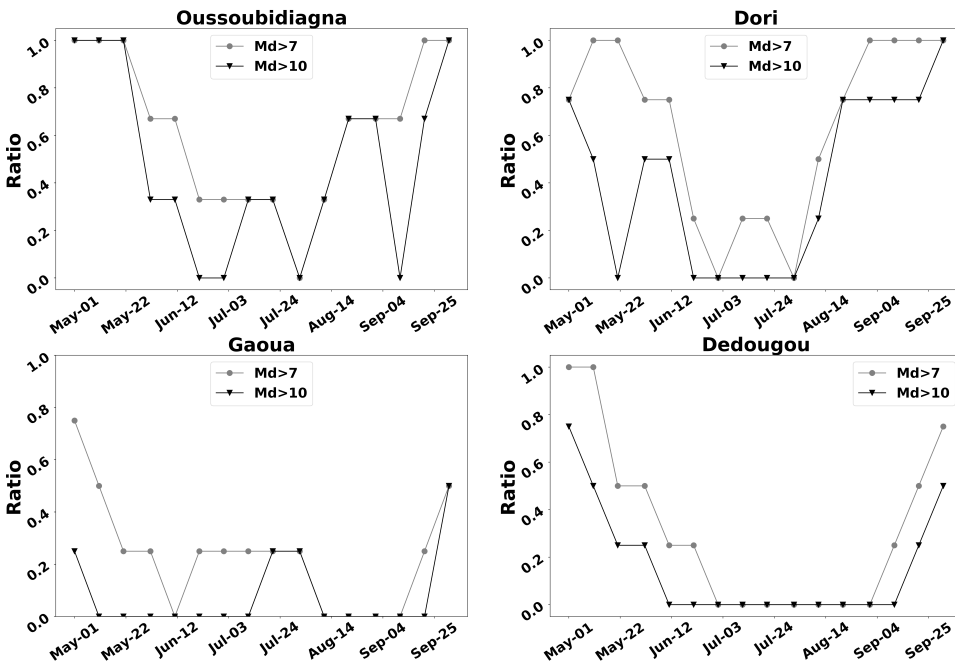


Figure 3.3: Ratio of maximum dry spells (Md) exceeding 7 and 10 days within 30 days after a specific date at four selected locations. The ratio is defined as the number of years a maximum dry spell occurs over the three-year data period per location, following (Sivakumar, 1992).

onset, accounts for both rainfall and evapotranspiration, defined as an average of four consecutive rainy days exceeding 10 mm daily (LO10mm) (Gbangou et al., 2019).

3.3.2. THE FAO CROP MODEL, AQUACROP

Crop development and yield response were computed using AquaCrop, an FAO crop model (Steduto et al., 2009). Crop modeling enables the evaluation of optimal conditions by simulating the plant in its environment, crop water requirement, and stresses at different stages of crop development. Thus, the safe sowing window was assessed by computing the response to different sowing dates from 1st May to 30th November for each season.

DESCRIPTION OF THE MODEL

Of the various crop models, AquaCrop was chosen as a user-friendly yet robust crop model, especially well suited for conditions where water is a key limiting factor for crop yield. It can be adapted to various conditions, agricultural water management practices, and planning (Hsiao et al., 2009; Vanuytrecht et al., 2014). The model uses a relatively limited amount of input data and is widely used in regions similar to WA (Abedinpour et al., 2012).

In AquaCrop, daily crop biomass is associated with the transpired water through biomass water productivity (Raes et al., 2009). Hence, the water-driven growth engine of

AquaCrop simulates the crop green canopy cover (CC in %) on daily time steps from crop emergence through the development and senescence of the canopy, while the root system develops and deepens. Transpiration is then converted into biomass accumulated every day using a crop-specific water productivity parameter WP^* (3.1) normalized for reference evapotranspiration:

$$B_i = WP^* \cdot \sum \left(\frac{Tr_i}{ET_{o,i}} \right) \quad (3.1)$$

where, at day i , B_i is the aboveground biomass (g), WP^* is the normalized crop water productivity (g of biomass per m^2), Tr_i is the transpiration (mm), and $ET_{o,i}$ is the evaporative demand of the atmosphere (mm).

This normalization makes WP^* a parameter applicable to a wide range of climates (Steduto et al., 2009). After the biomass is calculated by accumulation, the yield (Y) is partitioned from flowering using 3.2 via the harvest index (HI in %). We obtain the following:

$$Y = HI \cdot B \quad (3.2)$$

As a water-driven model, AquaCrop introduces the effects of water stress, which affects each component of the model. The water stress response is expressed as a stress coefficient K_s that modifies the simulated component. It varies in value from 1 (no stress) to 0 (full stress) as a function of the total available water (TAW) (Raes et al., 2009). Above an upper threshold of soil water content, the water stress is considered to be absent, and K_s is 1. Below a lower threshold, the stress is at its full effect and K_s is 0. The water deficit response is expressed through stress coefficients that progressively slow down canopy expansion, reduce stomatal conductance and transpiration, trigger and accelerate canopy senescence, decrease root deepening, and affect the harvest index depending on stress level, timing, and duration.

AquaCropv6.1 was used in this analysis, which requires as input weather data (precipitation, max, and min temperature, ET_0 , CO_2 concentration), soil information (soil profile, textures, and hydraulic properties of each layer), crop information (phenology, plant density, canopy cover, max root depth), and management information (irrigation schedule, application of mulches, water table).

PARAMETERIZATION OF THE MODEL

We considered a water-sensitive crop, 90 days maturation maize, as a suitable crop that is widely grown in the region. The aim was to run the Aquacrop model under different weather patterns observed across the WA region in order to investigate the impact of varying rainfall patterns on crop yields under rainfed farming. Considering the large number of parameters in Aquacrop and the scarce field data from the region, a formal model calibration of this regional yield study is not feasible, as has been acknowledged in (Abedinpour et al., 2012; Akumaga et al., 2017; Hsiao et al., 2009; Ran et al., 2018). Instead, we calibrated AquaCrop by choosing realistic parameter values determined in field trial studies in the region. We used default conservative parameters provided by (Hsiao et al., 2009; Raes et al., 2018) and chose realistic parameter values determined and validated in field trial studies across the region (Akumaga et al., 2017) and areas with similar agro-climatic conditions (Nyakudya and Stroosnijder, 2014) for maize

simulation, presented in Table 3.2. The model was further fine-tuned (see Table 3.3 for non-conservative parameters based on (Abedinpour et al., 2012)) to best approximate yield ranges observed in previous studies under rainfed conditions in WA (Galford et al., 2020; MoFA, 2010; Shelia et al., 2018). We incorporated information from specific regions collected by the project Global Yield Gap Atlas (GYGA), such as actual on-farm yield under rainfed conditions at the finest available resolution (sub-district, district or municipality; see Table 3.4).

Table 3.2: Conservative maize parameters (from (Hsiao et al., 2009) used in the AquaCrop simulations).

Parameters Description	Value	Units or Meaning
Base temperature	8	°C
Cut-off temperature	30	°C
Canopy cover per seedling at 90% emergence (CC_o)	6.5	cm^2
Maximum canopy cover (CC_x)	-	function of plant density
Canopy growth coefficient (CGC)	1.3	% increase per growing degree day (GDD)
Crop coefficient for transpiration at $CC = 100\%$	1.03	full canopy transpiration relative to ET_0
Decline in crop coefficient after reaching CC_x	0.3	% decline per day due to leaf aging
Canopy decline coefficient (CDC) at senescence	1.06	% decrease in CC relative to CC_x per GDD
Water productivity (WP)	33.7	$g(\text{biomass})\ m^{-2}$, function of atmosphere CO_2
Leaf growth threshold p-upper	0.14	as fraction of TAW, above which leaf growth is inhibited
Leaf growth threshold p-lower	0.72	leaf growth stops completely at p-lower value
Leaf growth stress coefficient curve shape	2.9	moderately convex curve
Stomatal conductance threshold p-upper	0.69	above this stomata begin to close
Stomatal stress coefficient curve shape	6.0	highly convex curve
Senescence stress coefficient p-upper	0.69	above this early canopy senescence begins
Senescence stress coefficient curve shape	2.7	moderately convex curve
Coefficient, inhibition of leaf growth on HI	7.0	HI increased by inhibition of leaf growth at anthesis
Coefficient, inhibition of stomata on HI	3.0	HI reduced by inhibition of stomata at anthesis

The normalized WP^* was set to $15.3\ g\ m^{-2}$ (inbuilt severe stress conditions), implying 54% reduction of WP^* (53% in (Akumaga et al., 2017)) as compared to the default values for C4 crops ($30\ g\ m^{-2}$ to $35\ g\ m^{-2}$). This value of WP^* describes the reduction in water productivity and relative biomass observed in arid and semi-arid regions (Akumaga et

Table 3.3: Non-conservative parameters adjusted (*) based on (Abedinpour et al., 2012) for 90 days maturation Maize and (Akumaga et al., 2017; Nyakudya and Stroosnijder, 2014).

Parameters Description	Value	Units or Meaning	Source Values
Time from sowing to maturity	90 (Fixed)	Day	97 (Abedinpour et al., 2012)
Time from sowing to emergence	6	Day	6
Time from sowing to start of canopy senescence	70*	Day	72
Time from sowing to flowering	48*	Day	52 (Abedinpour et al., 2012)
Duration of flowering	10	Day	10
Time from sowing to maximum rooting depth	80*	Day	-
Maximum effective rooting depth, Z	1.0	meter	1.0
Reference harvest index, HI	40	%	40 (Akumaga et al., 2017)
WP* reduction	54*	%	53
CCx under soil fertility stress	45*	%	40–77
Time to maximum canopy cover (CCx)	56	Day	Automated or
Building up of HI	25	Day	recommended by
Minimum effective rooting depth, Zn	0.3	meter	AquaCrop (FAO)
Plant population	40,000	Plant/ha	
N fertilizers levels	0 (No input)	N kg/ha	Expert
Weeds management	12	% coverage	knowledge

al., 2017). In the rainfed context of WA and based on field measurements, Akumaga et al. (2017) calibrated WP* with a 53% reduction (15.8 g m^{-2}) with respect to its default value (33.7 g m^{-2}) to achieve relatively small errors (4% at calibration, 8% at validation). Thus, without access to field experimental data, the same values were used in our simulations, as our stations are located in the same agroecological regions as the station where the study was performed.

Additionally, management constraints (limited soil fertility and weed control management) were implemented to represent the agricultural situation of rainfed small-holder farming in WA. AquaCropv6.1 offers the possibility of simulating the effects of soil fertility and limitations induced by weed stresses (Raes et al., 2018). We followed Akumaga et al. (2017) when it comes to fertility levels and weed pressure settings by choosing poor fertility and a 53% yield reduction due to weed pressure. They obtained relatively small errors. Here, we expect larger errors in general, as the specific circumstances vary widely over the region; however, we expect the obtained yields to be realistic and typical. To account for these limitations, the model was set to the inbuilt poor soil fertility level (i.e., total soil fertility stress of 66%) corresponding to no application of fertilizer.

Table 3.4: Comparison of actual yield ranges (from (GYGA), 2007–2011) to actual yield ranges of maize simulated with AquaCrop using the TAHMO dataset (2018–2020).

Country	Station	5 Recent Years Sowing		Mean Actual Yield Nearest Station		Simulated Yield for Sowing Dates (t/ha)
		Available	Dates	[Range] (t/ha)	in TAHMO	
Burkina Faso	Bogande	2007–2011	16–24 Jun	0.99 [0.8–1.4]	Bogande	0–1.5
	Boromo	2007–2011	11–23 Jun	1.46 [0.9–1.7]	Boromo	1.3–1.5
	Dedougou	2007–2011	02–16 Jun	1.46 [0.9–1.8]	Dedougou	1.4–1.5
	Gaoua	2007–2011	02–08 Jun	1.08 [0.7–1.4]	Gaoua	1.5
Ghana	Wa	2007–2011	02–24 Jun	1.3 [1.0–1.5]	Daffiama	1.1–1.5
	Bolgatanga	2007–2011	01–08 Jun	1.39 [0.8–1.7]	Pusiga	1.4–1.5
	Yendi	2007–2011	01–04 Jun	1.5 [1.2–1.8]	Tamale	1.5
Nigeria	Maidu	2006–2010	01–05 Jul	1.1 [0.9–1.1]	Unimaid	1.1–1.6
Mali	Dag Dag	2007–2011	02–07 Jul	2.1 [0.7–3.9]	Oussoubidiagna	0–1.5
	Senou	2007–2011	10–26 Jun	1.9 [0.7–3.6]	Sirakoro	1.4–1.5
	Koutiala	2011–2013	11–25 May	2.3 [2.2–2.5]	Finkoloni	0–1.5
	San	2007–2011	11–17 Jun	1.5 [0.3–2.5]	Somo	0–1.5

3.4. RESULTS AND DISCUSSION

3.4.1. CROP MODEL PERFORMANCE

Table 3.4 compares yield data from the Global Yield Gap Atlas (GYGA) and simulated yields by the Aquacrop model for the same or nearest locations to the TAHMO stations we used in our study. Simulated yields were obtained using AquaCrop, applying the same sowing dates and the same climate data provided in the GYGA database. The AquaCrop results capture the range of actual yields reported at each location in the GYGA database. Discrepancies are found for the stations in Mali (highest average yields in WA (Abate et al., 2015)), likely explained by management practices and soil fertility differing from the settings used in the model (Tittonell and Giller, 2013).

Overall, yields in the Sudanian region of WA range from 0 t ha⁻¹ (crop failure) to a maximum of 1.7 t ha⁻¹. This is in agreement with yields previously reported in the literature (Galford et al., 2020; MoFA, 2010; Shelia et al., 2018). Figure 3.4 shows the simulated versus actual yields for the locations listed in Table 3.4. The associated metrics, root mean square error ($RMSE = 0.16$ t/ha), and coefficient of determination ($r^2 = 0.52$) indicate that the simulated yields fit and correlate well with the observed actual yields on-farm. Hence, the set of parameters used here (Tables 3.2 and 3.3) adequately represents farming practices in WA. Moreover, the nutrient level considered (0 N kg/ha) reflects the poor soil quality of most farmlands, which are typically burned after the harvest with no or little addition of fertilizers (Sultan et al., 2014). Table 3.4 shows a typical example of an AquaCrop run with weed control and normal soil fertility. Clearly, these values are much higher than what is typically found on smallholder farms in the region (Galford et al.,

2020; MoFA, 2010). Very important is that in this case the relative results show that certain years and sowing dates do greatly reduce the yield (see Table 3.4-Oussoubidiagna).

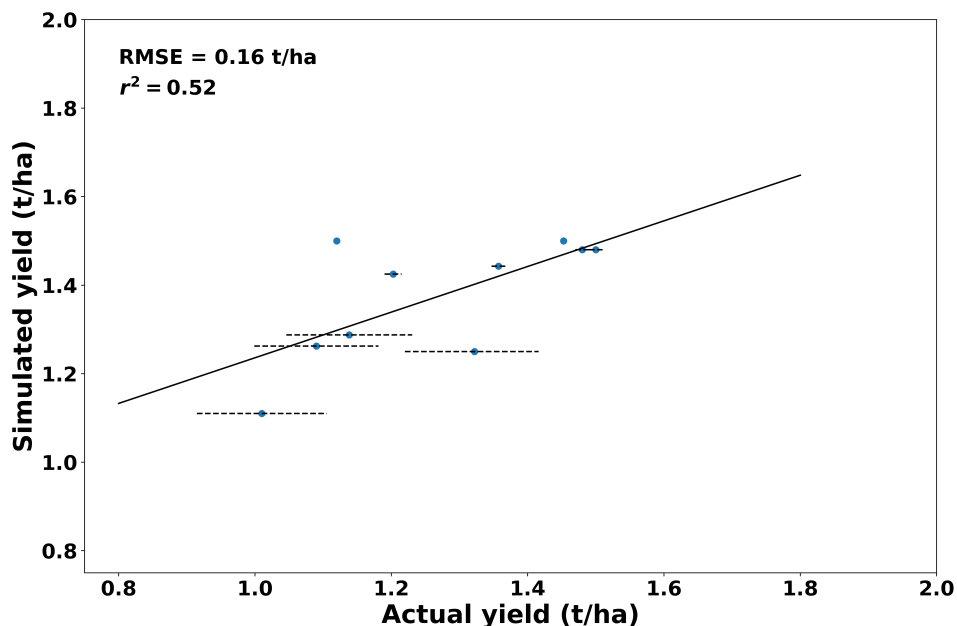


Figure 3.4: Correlation fit for actual on-farm yield versus simulated yield computed at the same or nearest locations to the TAHMO stations used in this study.

3.4.2. YIELD DISTRIBUTION IN RESPONSE TO VARYING SOWING DATES

Crop response varies with the sowing date as a result of varying weather conditions, in particular, the occurrence of dry spells during the growing stages of the crop. Figure 3.5 shows the variation of yield response for sowing dates ranging from 1 May to 30 November at four selected stations across the region. For stations Oussoubidiagna, Gaoua, and Dedougou, yields of 1.4–1.6 t ha⁻¹ are achieved for a window of sowing dates between 20 June and 20 August. Variability in the width of the sowing windows occurs at all three locations; at Oussoubidiagna, one of the years even shows a very narrow window wherein yields of no more than 0.95 t ha⁻¹ are reached. At Dori, the driest location, a very narrow window of less than a month is observed, with yields varying between 1.3 and 1.6 t ha⁻¹. Yields decrease sharply beyond this window and drop to complete yield failure within a few weeks. This makes the selection of an appropriate sowing date particularly important. We stress again that these results should not be taken as absolute yields with known error distributions, but rather as relative yields as a function of location and planting date.

Figures 3.3 and 3.5 indicate that sowing early in May after the first rains is a risky strategy for several locations, as the crop is likely to experience water stress, especially in dry years. In addition, at the beginning of the rainy season, regardless of the inten-

sity of the rains, two important phenomena can be observed. First, soil evaporation is more important than transpiration due to the dry state of the soil after a long dry season (November to March) (Wolka et al., 2018). Second, the soil is still building up water storage to sustain crop growth and overcome subsequent rainfall deficits. This highlights the importance of soil water storage and of different water conservation techniques used in agriculture with proven effects on yield production (Wolka et al., 2018).

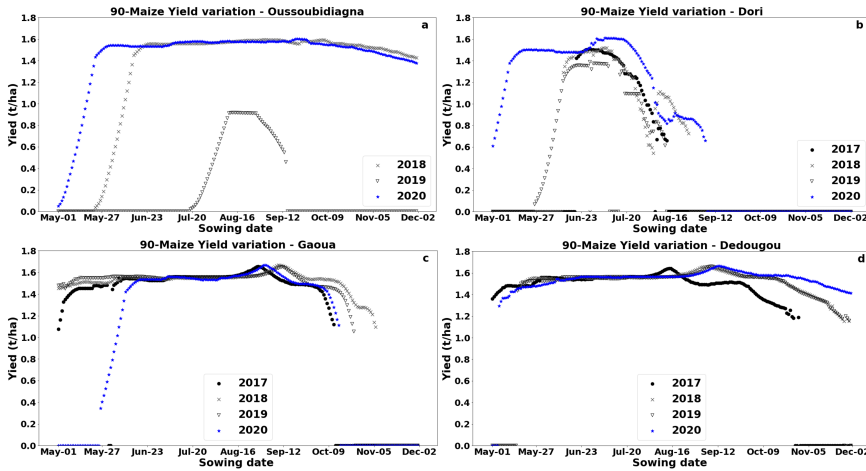


Figure 3.5: Variation in yield response for 90-day maize for each date of the sowing window from 1st May to 31st November at four selected locations: (a) Oussoubidiagna, (b) Dori, (c) Gaoua, and (d) Dedougou.

Therefore, it seems that waiting for several rain events and sowing late might solve the sowing challenge. However, the graphs suggest that at locations such as Dori, waiting too long can lead to reduced yield (failure). This is in agreement with the northward/southward movement of the Inter-Tropical Convergence Zone (ITCZ) in WA (Sultan et al., 2005). In fact, the northward shift of the ITCZ (rainfall maximum) to the Sudanian region occurs around May, while the inverse movement happens around mid-August, leading to a decrease in rainfall. This implies that sowing beyond the adequate sowing window may only extend the growing season beyond the rainy season and lead again to water stress at the end of the crop development (Waongo et al., 2014). Hence, it matters how sowing strategies are determined. A safe sowing window can be identified for recommendation purposes. Defining the safe sowing window for each of the locations, understanding the reasons behind yield reduction, along with how well the different definitions of the onset perform, is therefore crucial to minimizing crop losses.

3.4.3. COMPARING YIELD RESPONSE FOR THREE LOCAL ONSET APPROACHES

Sowing dates based on three different local onset approaches vary from as early as the first week of May to mid-September (Figure 3.6), reflecting the northward shift of the sowing dates, which follows the northward migration of the ITCZ. LO20mm and FP20mm generally occur earlier in the season (50% and 66% of the sowing dates in May, respec-

3

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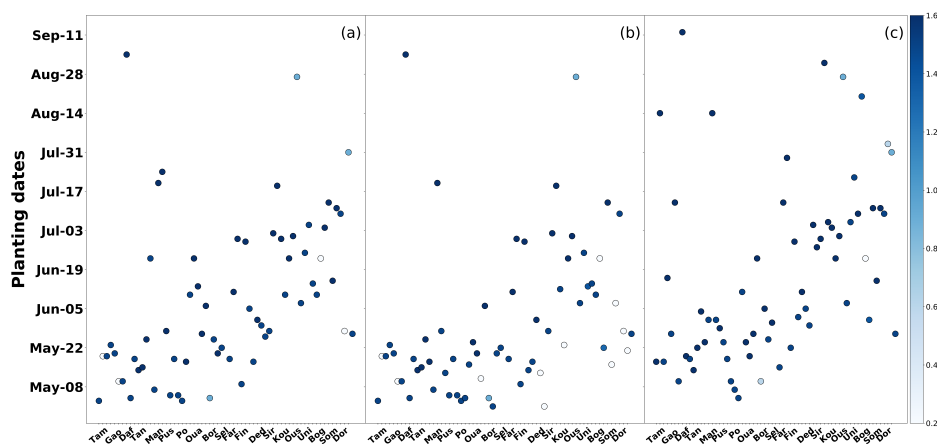


Figure 3.6: Yield response for sowing dates according to three local onset approaches. The shading of each marker represents the amount of yield [0–1.7 t ha⁻¹] achieved at each location. (a) LO20mm, (b) FP20mm, (c) LO10mm

The 30-day control period incorporated in the LO20mm approach seems to provide an extra buffer to prevent the crop from experiencing important water stress at early development stages, protecting it from complete failure (Marteau et al., 2009; Sivakumar, 1992).

3.4.4. EFFECTS OF WATER STRESS ON CROP DEVELOPMENT

The analysis of stress effects and water content in the soil provides insights into yield failure when considering a specific onset date. Figure 3.7 shows the daily crop response (1. biomass and yield build-up, 2. stress effects, 3. rainfall distribution, and 4. soil water content) when considering LO20mm and a sowing date within the safe window at Gaoua in 2020. Despite both the water threshold and control period criteria being satisfied according to LO20mm (10 May 2020), the crop experiences severe stress during the first month of its development (Figure 3.7(a2)). Shortly after sowing, most rainfall is lost directly due to evaporation. Consequently, the soil water content in the effective root zone (W_r) remains at the permanent wilting point (PWP). As a result, the crop ex-

periences persistent and intense water stress (between 50% and 100%) after emergence, affecting leaf expansion and stomatal conductance, and disabling the production of any biomass. This triggers early canopy senescence, leading to crop failure by June 24. The same scenario is observed for FP20mm.

Alternatively, for the sowing date of 4th July 2020, within the safe sowing window (Figure 3.7b), the soil water content is at field capacity upon sowing, and oscillates around the same water content level throughout the growing season. Although the crop experiences a dry spell of 8 days shortly after sowing, leading to 55% stress on leaf expansion and 23% stress on stomatal conductance, subsequent rains soften the effects, preventing crop failure. Moreover, the water storage built up from the beginning of the rainy season up to the sowing date enables the crop to overcome two other dry spells of two weeks at the beginning of August (vegetative stage) and one week during yield formation. The total stress experienced at the end of the season amounts to 1% stress on both leaf expansion and stomatal conductance and maximum yield was achieved. Similar results were observed for LO10mm (sowing date 13 July 2020).

These results confirm that enabling the soil to build up sufficient water storage is a safe approach to prevent both false starts and harmful dry spells during the growing season. Benoit (1977) recommended the same approach to farmers in the Sudan-savanna region of Nigeria. This approach helps protect the crop from severe water stress during the two most critical stages of emergence and flowering.

3.4.5. SAFE SOWING WINDOW ACROSS WEST AFRICA

The safe sowing window is defined as the sowing dates during the rainy season that lead to at least 90% of maximal yield at a particular location. Figure 3.8 shows the safe sowing window computed using AquaCrop for all stations in 2020 (see Figures 3.9 and 3.10 for the years 2018 and 2019, respectively). The start of the safe window follows the south-north gradient of maximum rain and a second northwestward shift. In the savanna region, with relatively high and well-distributed rainfall, the start of the window is nearly invariant and takes place in May, while a delay is observed until June for the western part and July for the semi-arid zone.

To account for the alternate behavior of wet/dry years within the datasets, we define the safe window in the context of this analysis as the intersection between all windows securing optimal yield at a location. Thus, we observe a safe window on average from the beginning of June (June 4th) in the savanna region, mid-June, and the last week of June for the western part and the semi-arid regions, respectively. The end of the window and therefore its length seems wide for the whole region except for the semi-arid region where, beyond the month of July, the crop is exposed to dry spells during the late stages of crop development (see Figure 3.5—Dori). Marteau et al. (2011) noticed the same phenomenon when simulating the yield response of pearl millet (*Pennisetum glaucum*) in southwest Niger. These results corroborate previous studies that observe the same shift of the onset: a northward shift of the onset from mid-May in south Burkina Faso to late July in central-northern Mali (Marteau et al., 2009), and optimal sowing window from early May to early July, respectively, from the south to the north of Burkina Faso (Waongo et al., 2014). Ati et al. (2002) noticed that for the region where Unimaid is located that sowing between June and early July would help combat false start using a method based

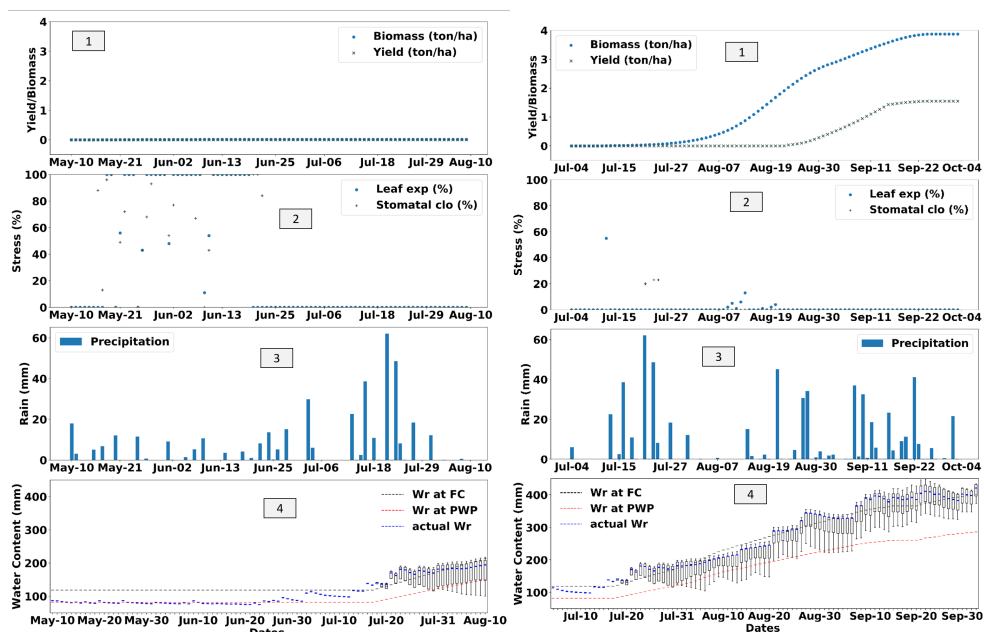


Figure 3.7: Crop yield and biomass accumulation (1), stress effects on leaf and stomatal closure (2), daily rainfall (3), and water content in the effective rooting zone (4) for sowing dates according to LO20mm on 10 May 2020 (left), and date within safe sowing window (4 July 2020)—Gaoua (right). Actual Wr is the water content in the effective root zone compared to water content at field capacity (FC) and at permanent wilting point (PWP).

on rainfall and evaporation.

Farmers often do not have access to the accurate rainfall information needed in order to apply the local onset definitions discussed in this paper. The safe sowing windows serve as guidelines for the different zones of the Sudanian region. It is therefore recommended that sowing moments are delayed in the southern regions until at least mid-June, while in the semi-arid region (drier), sowing must take place in July for drought-sensitive crops such as maize. Delaying the sowing ensures that considerable consecutive rains have fallen, that the high vulnerability to dry spells at the start of the season is avoided, and that there is enough time to build up soil water storage.

3.5. CONCLUSIONS

In this paper, the FP20mm approach currently used by most farmers is shown not to be a reliable sowing criterion, as 12 cases out of 64 resulted in complete yield failure. Yield losses are explained by a high likelihood of dry spells occurring shortly after the first rains within the sowing date range of FP20mm. By contrast, LO20mm and LO10mm result in 57 and 54 out of 64 cases, respectively, reaching optimal yield, which is at least 90% of maximum yield at the location. However, these two approaches pose challenges for smallholder farmers because many of them do not have access to reliable rainfall in-

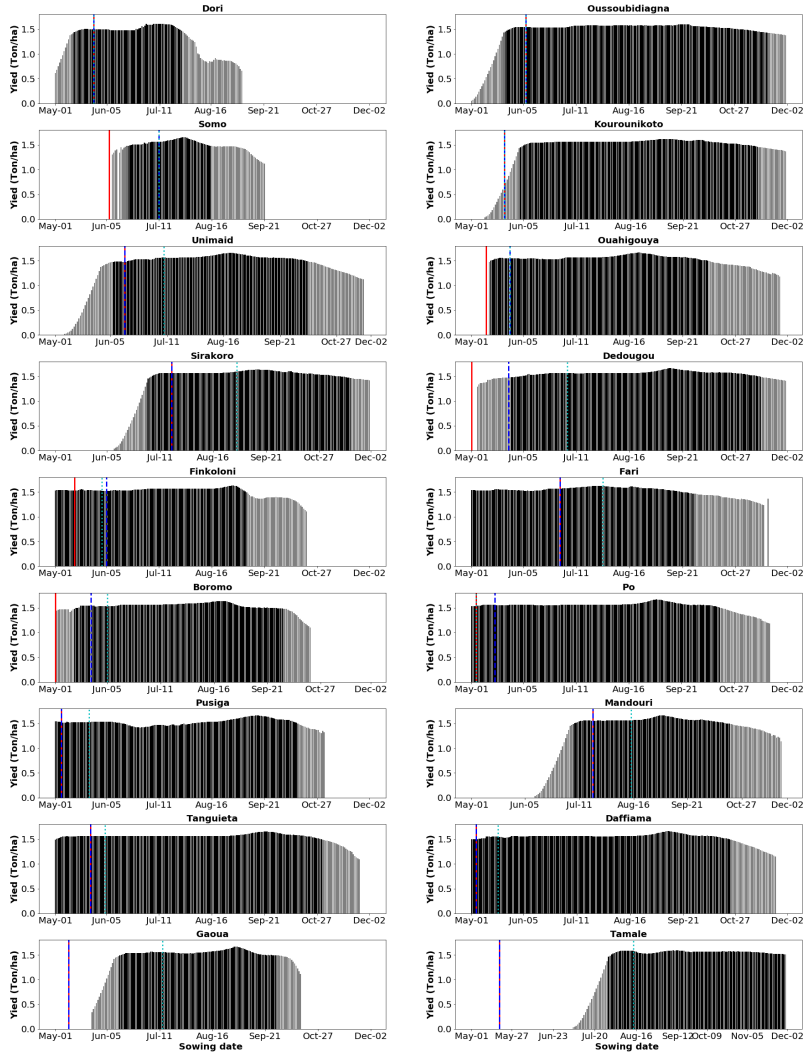


Figure 3.8: Variation of yield response to each date of the sowing window from 1st May to 31st November in 2020 expressed as a bar chart for the available locations. The dark bars represent the safe windows and the vertical lines represent the different sowing based on the three definitions: (i) red for FP20mm, (ii) blue for LO20mm, and (iii) cyan for LO10mm.

formation. Moreover, the control period of the LO20mm approach, no 7-dry-spell in 30 days following the first two rain events of 20 mm, is hardly practical. It requires monitoring for dry spells for a period of 30 days before making a decision, which may lead to sowing too late.

On the other hand, our results based on computed yields for twenty stations across the region over a period of three years (2018-2020) for showing dates between May and

November show that there is a safe window that ensures optimal yields in 97% of the cases. Delaying the sowing date beyond the onset of the rainy season, to mid-June in the lower latitudes (savanna) and the western part of the region, and to July for the higher latitudes (semi-arid region), ensures optimal yields in nearly all cases. Only in two cases is the yield reduced by half due to exceptionally dry years. Delaying the sowing dates in this way helps to avoid the false start of the rainy season and ensures that there is enough soil water storage to overcome dry spells, especially during sensitive stages of crop development. We are aware that other factors, such as labor availability and market prices, affect the choice of sowing date. Nonetheless, in the context of limited rainfall information available to farmers, we recommend these safe sowing windows for short-term and drought-sensitive cereals such as maize cultivars that have a 90-day growth cycle.

3.6. APPENDIX: VARIATION OF THE YIELD RESPONSE OF 90-DAY MAIZE

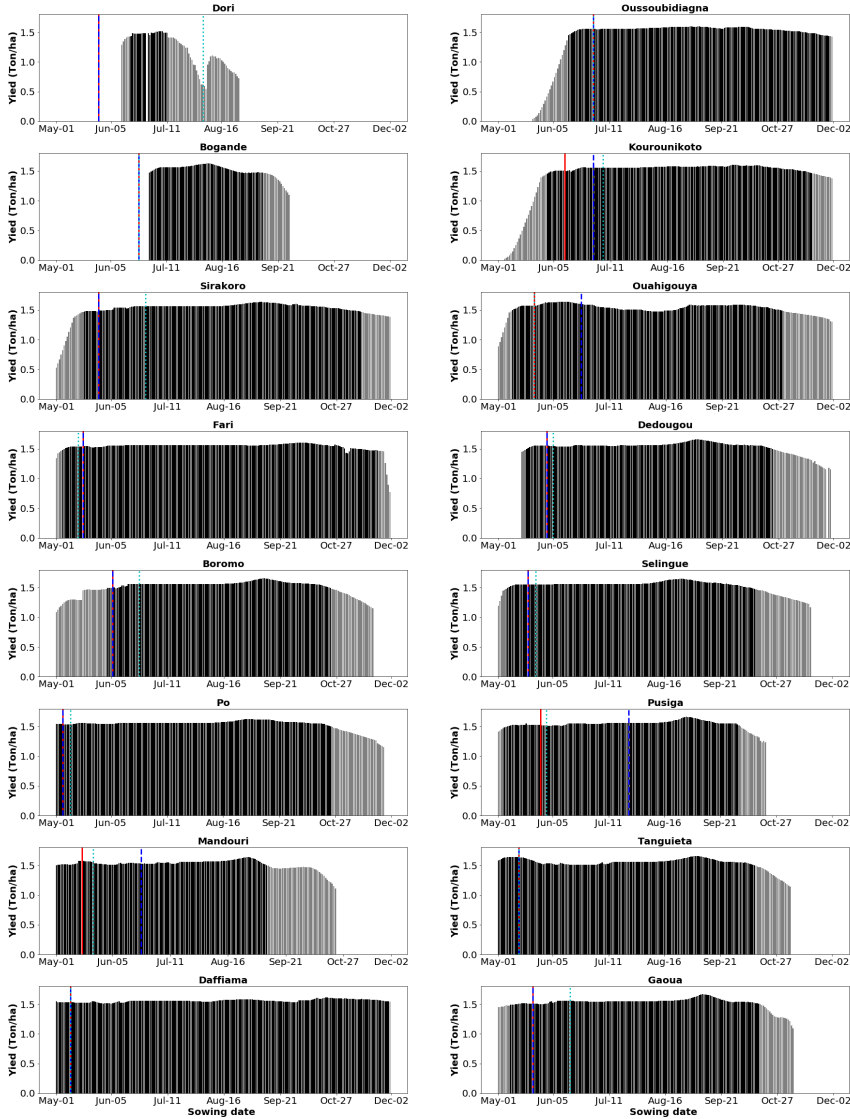


Figure 3.9: Variation of yield response to each date of the sowing window from 1st May to 31st November in 2018 expressed as a bar chart for the available locations. The dark bars represent the safe windows and the vertical lines represent the different sowing based on the three definitions: (i) red for FP20mm, (ii) blue for LO20mm, and (iii) cyan for LO10mm.

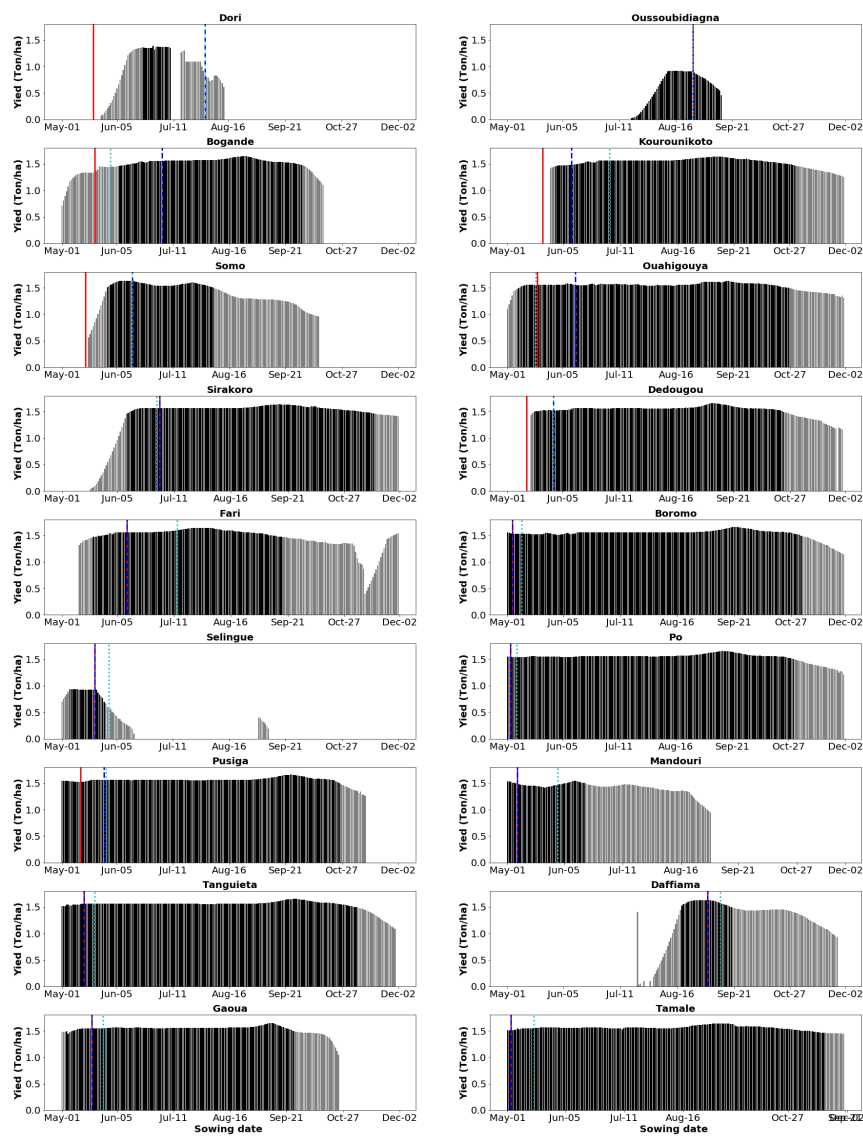


Figure 3.10: Variation of yield response to each date of the sowing window from 1st May to 31st November in 2019 expressed as a bar chart for the available locations. The dark bars represent the safe windows and the vertical lines represent the different sowing based on the three definitions: (i) red for FP20mm, (ii) blue for LO20mm, and (iii) cyan for LO10mm.

4

SAFE SOWING WINDOWS FOR SMALLHOLDER FARMERS IN WEST AFRICA IN THE CONTEXT OF CLIMATE VARIABILITY

*Climate variability poses great challenges to food security in West Africa, a region heavily dependent on rainfall for farming. Identifying sowing strategies that minimize yield losses for farmers in the region is crucial to securing their livelihood. In this paper, we investigate three sowing strategies to assess their ability to identify safe sowing windows for smallholder farmers in the Sudanian region of West Africa (WA) in the context of a changing climate. The GIS version of the FAO crop model, AquaCrop-GIS, is used to simulate the yield response of maize (*Zea mays* L.) to varying sowing dates throughout the rainy season across WA. Based on an average of 38 years of data per grid cell, we identify safe sowing windows across the Sudanian region that secure at least 90% of maximal yield. We find that current sowing strategies, based on minimum thresholds for rainfall accumulated over a period that are widely applied in the region, carry a higher risk of yield failure, especially at the beginning of the rainy season. This analysis shows that delaying sowing for a month to mid-June in the central region (east of Lon 8.5° W), and to early August in the semi-arid areas, is a safer strategy that ensures optimal yields. A comparison between the periods 1982–1991 and 1992–2019 shows a negative shift for LO10 mm and LO20 mm, suggesting a wetter regime compared to the dry periods of the 1970s and 1980s. On the contrary, we observe a positive shift in the safe window strategy, highlighting the need for precautions due to erratic rainfall at the beginning of the season. The precipitation-based strategies hold a high risk, while the safe sowing window strategy, easily accessible*

This chapter is based on: **Agoungbome, S.M.D.**; ten Veldhuis, M.-C.; van de Giesen, N. *Safe Sowing Windows for Smallholder Farmers in West Africa in the Context of Climate Variability*. Climate 2024, 12, 44. (Agoungbome et al., 2024).

to smallholder farmers, is more fitting, given the current climate.

4.1. INTRODUCTION

There is growing pressure on water resources to sustain food production and to reduce the food security gap in several parts of the world (Berners-Lee et al., 2018; Dinar et al., 2019; Hanjra and Qureshi, 2010). In particular in West Africa, rapid population growth and the central role of rain-fed agriculture for food production have exacerbated food insecurity (FAO et al., 2019). Climate change may increase threats to the already vulnerable communities. With more and more vulnerable regions being affected by increasingly extreme climatological conditions, such as drought and flooding, many vital sectors are impacted, and adaptation measures are of paramount importance (Liu et al., 2023; Tzachor et al., 2023; Wallach et al., 2023). Climate variability in West Africa and the subsequent uncertainties in the context of a changing climate have been the focus of several studies (Amekudzi et al., 2015; Biasutti, 2019; Manzananas et al., 2014; Nicholson et al., 2018; Wang and Alo, 2012). This has led to providing remarkable insights and knowledge about the characteristics of the rainy season (onset, duration, and cessation) and its implication for local farmers to support adaptation measures.

In the farming systems of West Africa, more than 90% of farmers depend on seasonal rainfall, which guides the planning of farming and the selection of crop types (drought-resistant/tolerant) and varieties (long/short maturation) (Adjei-Gyapong and Asiamah, 2002; Ismaila et al., 2010). As a result, the success (or failure) of a growing season strongly rests on identifying the right (or wrong) planting date. However, due to the lack of accurate climate information services, the sector is becoming more vulnerable, and farmers have been reporting the phenomenon of the so-called "false start" of the rainy season (Sultan and Gaetani, 2016). The false start or "false onset" is a consequence of the unpredictable rainfall pattern and is characterized by erratic rain events at the beginning of the season followed by intermittent dry spells of various lengths (Laux et al., 2008; Silungwe et al., 2019).

The issue of the false start of the rainy season in the savanna region has not only challenged local knowledge but has also alarmed agro-meteorologists. As a result, two approaches to safe sowing strategies at a local scale are available in the region, each with its uncertainties: a precipitation-based strategy and a crop water requirement-based strategy. The precipitation-based strategies consider empirical thresholds of accumulated rainfall totals over a period of time (control period) to identify the start of the rainfall season and ensure sufficient water availability for crop development (Ati et al., 2002; Marteau et al., 2009; Yamada et al., 2013). Crop water requirement-based strategies use crop simulation modeling to evaluate expected yields to determine appropriate sowing windows that minimize stresses and optimize crop yield (Agoungbome et al., 2023).

How well do these sowing strategies determine realistic sowing dates, and are they able to identify the false starts of the rainy season? Which strategy results in optimal yields, and what are the associated risks attached? This paper investigates these crucial questions and provides several suggestions as to how farmers can apply them most effectively. Using 38 years of weather information across the WA region, we evaluated the yield responses based on three sowing strategies: two strategies based on rainfall amounts in a certain period and a so-called safe sowing window strategy based on predicted yields through crop modeling. The safe sowing window method is more sensitive to dry spells during the growing season. To calculate yield predictions in response to

rainfall variability, we used AquaCrop-GIS, the GIS version of the FAO crop model. After an overview of the methodology used, we will analyze the inter-annual as well as spatial variability of each strategy, the impact of climate change on their ability to determine realistic sowing dates, and the risk of using any of these strategies.

4.2. DATA DESCRIPTION

4.2.1. STUDY AREA

The study area covers the Sudanian agro-climatological region of West Africa located between latitudes 8°N and 15°N, which is characterized by a unimodal rainy season per year (see Agoungbome et al., 2023). The study area covers the savanna region of West Africa extending into the Sahel region. Rainfall is convective and is associated with a northward latitudinal gradient associated with the Inter-Tropical Convergence Zone (ITCZ) (Aryee et al., 2018). The area covers locations between Chad (to the east) and Senegal (to the west).

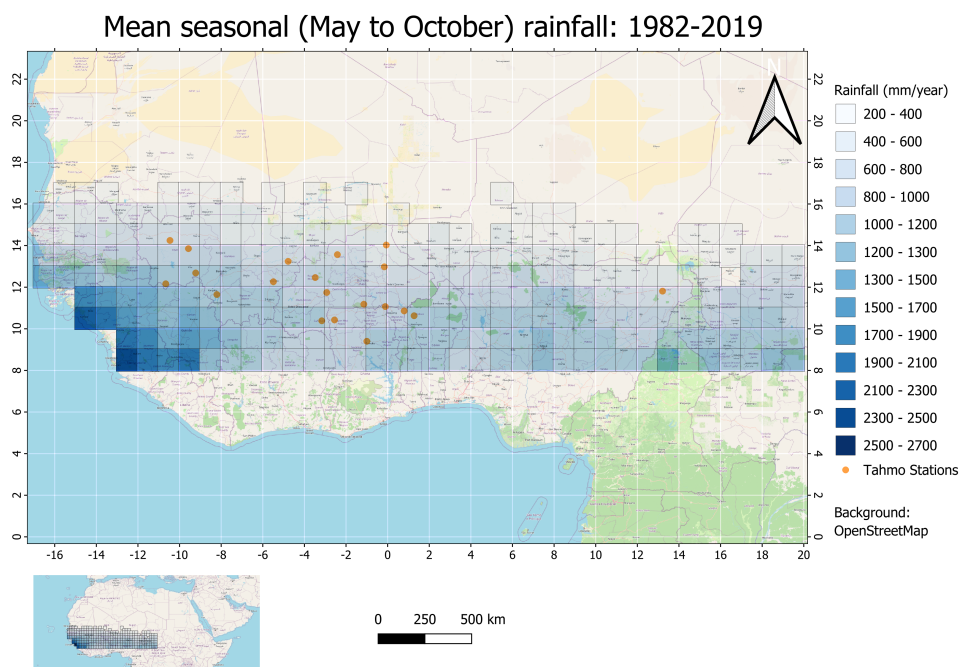


Figure 4.1: Gridded map of the study area in West Africa and mean seasonal rainfall (1 May to 31 October) of each grid cell. The grid represents the latitude and the longitude. The yellow dots represent the location of the TAHMO weather stations (see Agoungbome et al., 2023)

4.2.2. DATA SOURCES

The data sources required to run the model simulations in Aquacrop-GIS include rainfall, temperature, humidity, solar radiation and wind speed (to calculate reference evap-

otranspiration), soil information (depth, texture, and physical properties), and information on management practices (sowing windows, soil fertility level, application of mulches, etc.). Rainfall information is extracted from the Global Precipitation Climatology Centre (GPCC), version 2020, and covers a period of 38 years (1982 to 2019) with a resolution of 1° (Ziese et al., 2020). The dataset is operated by the German Weather Service (DWD), which collects meteorological data from across the globe, and it comprises daily in situ precipitation information. Taking stock of the water, energy, and climate change (WATCH) Forcing Data methodology applied to ERA5 (WFDE5), the WFDE5 provides daily temperature, humidity, wind speed, as well as surface downwelling short/long-wave radiations necessary to compute reference evaporation, E_{ref} . The Makkink equation (de Bruin and Lablans, 1998) is used to compute reference evapotranspiration with satellite data and is validated against the evapotranspiration computed using ground measurements from the TAHMO database (van de Giesen et al., 2014a).

Soil information is derived from the Africa SoilGrids - Texture database, which comprises the textural class at six depth intervals up to 200 cm over the African continent at a resolution of 250 m. The information from the gridded product is combined with the AquaCrop default soil dataset for several soil classes to generate the soil profile of each grid cell. Information on management practices in the savanna region is the same as the details used in (Agoungbome et al., 2023) following interviews and discussions with farmers and expert agronomists in the northern regions of Benin and Ghana, including the current practice with respect to sowing timing.

4.2.3. SEASONAL VARIABILITY OF CLIMATE INDICES IN THE STUDY AREA

Annual rainfall in the region is highly influenced by the West African Monsoon (WAM) (Akinsanola and Zhou, 2020). After the collision of dry air masses from the Sahara and the warm and humid air from the Atlantic Ocean, rainfall is triggered along the West African coast, i.e., the Gulf of Guinea (Quagraine et al., 2020). Following a shift of the ITCZ at latitude 5°N , the rainfall maximum moves to the Savanna zone to 10°N (Fontaine et al., 2008; Gazeaux et al., 2011). Figure 4.1 shows the distribution of the mean seasonal rainfall across the region over the period of 1982 - 2019. Spatially, mean seasonal rainfall varies from about 1000 mm in the south of the region to less than 500 mm in the Sahel, reflecting the spatial and latitudinal variation of rainfall in the Sudanian region of West Africa (Lebel and Ali, 2009). The southwestern part of the study area, however, shows higher seasonal rainfall (± 2000 mm), which is associated with the highlands and the topography of the Fouta Djallon region in Guinea (Raj et al., 2019) and the mountains of Sierra Leone. Figure 4.2 shows the average seasonal rainfall and evapotranspiration. The unimodal pattern of the rainfall season varies from May to October. Most of the rain falls between June and September (80% and 91% on average for the savanna and the semi-arid zones, respectively) (Biasutti, 2019).

We observe that seasonal rainfall can meet evaporative demand in most locations across the region. In part of the region, the average monthly E_{ref} equals or exceeds monthly rainfall even during the rainfall season.

The long-term variation is shown in Figure 4.2.c at Lat 10.5°N , Lon -3.5°N . The dataset captures very well the drought period that the region experienced between the 1970s and 1980s in West Africa, followed by a recovery to varying degrees across the region at the

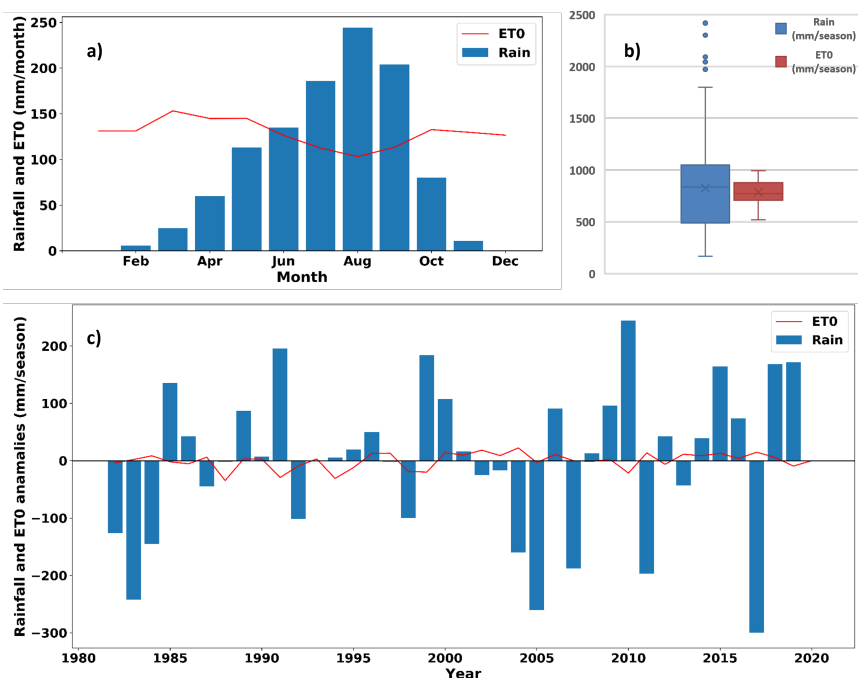


Figure 4.2: Rainfall and evapotranspiration distribution at Lat 10.5°N, Lon=-3.5°N: **a)** average monthly variation, and **b)** mean regional seasonal (May to October) variation, **c)** long-term seasonal variation between 1982 and 2019.

beginning of the 21st century (Nicholson et al., 2018; Sultan and Gaetani, 2016).

4.3. METHODS

4.3.1. SOWING STRATEGIES OF THE GROWING SEASON

Three sowing strategies are evaluated in this study following a previous investigation on the onset of the growing season in West Africa: two rainfall-based sowing strategies widely recommended in the literature and the safe sowing window strategy suggested in (Agoungbome et al., 2023), based on predicted yields through crop modeling, and thereby more sensitive to dry spells occurring during the growth season. Regarding the safe sowing window, for every specific location, the maximal achievable yield is evaluated using a crop simulation model (here, the FAO model AquaCrop). The “safe window” is thereafter determined by finding those sowing dates within the season that result in a yield that equals at least 90% of the maximum achievable yield of that location. The idea is to identify safe windows for sowing that ensure low yield losses for farmers, who have no or limited access to local rainfall information, as is required for the rainfall-based approaches. The first rainfall-based approach, also referred to as the Local Onset (of the rainfall season, LO) approach, LO20mm hereafter, defines the onset as one or two consecutive rainy days accumulating at least 20 mm with no 7-day dry spell occur-

ring during the next 30 days counted from the onset (Marteau et al., 2009). This sowing strategy approach prioritizes sufficient water availability and limits the occurrence of long dry spells at the early stages of crop development, but requires a long control period (30 days) before farmers can start planting. The second rainfall-based approach also referred to as agronomic onset, LO10mm hereafter, is defined as an average of four consecutive rainy days exceeding 10 mm daily (Gbangou et al., 2019). The focus of this approach is to identify the earliest moment that still ensures sufficient soil humidity to sustain seed germination after sowing (Huho, 2011; Marteau et al., 2011; Silungwe et al., 2019).

Based on field surveys and rainfall patterns in the WA region, we observed that the earliest possible time for farmers to sow their crops is the beginning of May. Knowing that the season runs until October/November and that various soil types have different water-holding capacities, our goal was to assess how the crop would respond to any planting date in that range. We chose to run the simulations at 5-day intervals for computational efficiency, as we ran the model simulations for the entire WA region. In a previous study for a selected number of locations, we used 1-day time intervals and found that the time response of maize crops to rainfall variability and dry spells is about 1 week. This is confirmed by another study for this region (Marteau et al., 2009).

4.3.2. THE FAO CROP MODEL AQUACROP

Crop development and yield response are computed using AquaCrop, the FAO crop simulation model (Steduto et al., 2009). The sowing window is evaluated by computing crop response to sowing dates ranging from 1st May to 30th November at five-day intervals at any location throughout the growing season.

DESCRIPTION OF THE MODEL: AQUACROP-GIS

AquaCrop, the FAO crop model, is a water-driven model that simulates daily crop biomass, which is associated with the transpired water through biomass water productivity (Raes et al., 2009). Hence, the water-driven growth engine of AquaCrop simulates the crop green Canopy Cover (CC in %) on daily time steps from crop emergence through the development and senescence of the canopy, while the root system develops from the minimum effective rooting depth Z_n and increases to the maximum rooting depth (Raes et al., 2009). Transpiration (4.1) is then converted into biomass accumulated every day, using a crop-specific water productivity parameter WP^* (4.2) normalized for E_{ref} .

$$Tr_x = CC^* \cdot Kc_{tr,x} \cdot E_{ref} \quad (4.1)$$

where CC^* is the adjusted canopy cover, and $Kc_{tr,x}$ is the coefficient for maximum crop transpiration. Further:

$$B_i = WP^* \cdot \sum \left(\frac{Tr_i}{E_{ref,i}} \right) \quad (4.2)$$

where, at day i , B_i is the above-ground biomass (g), WP^* is the normalized crop water productivity (g of biomass per m²), Tr_i is transpiration, and $E_{ref,i}$ is the evaporative demand of the atmosphere (mm).

This normalization of WP^* for evaporative demand of the atmosphere and air carbon dioxide concentration makes the parameter approximately constant for a given crop species and applies to a wide range of climates (Steduto et al., 2006, 2009). Once the biomass is calculated by accumulation, yield (Y) is partitioned from flowering using 4.3 via the harvest index (HI in %). We obtain the following:

$$Y = HI \cdot B \quad (4.3)$$

As a water-driven model, AquaCrop introduces the effects of water stress, which affects biomass development (slows canopy expansion and accelerates senescence), reduces yield build-up, and root deepening in extreme cases (Vanuytrecht et al., 2014). The water stress response is expressed as a stress coefficient K_s that modifies the simulated component and varies in value from 1 (no stress) to 0 (full stress) as a function of the total available water (TAW, the volume of water the soil can hold between field capacity and permanent wilting point) (Raes et al., 2009).

AquaCrop-GIS version 2.1, the multi-spatial version of the FAO crop simulation model AquaCrop (Steduto et al., 2009), was used to assess the regional level. It has been designed to facilitate the use of the model when a high number of simulations is needed, simplifying the task of generating input and project files and the management of output files (Lorite et al., 2015). The software generates the necessary input files, executes AquaCrop at each pixel/grid, elaborates on the results, and displays them in a geographic information system format. This simulation module of the software, however, uses AquaCrop version 4.1, which is less suitable for our study, since many upgraded functionalities in version v6.1 are missing, such as simulating calendar days and soil fertility levels. Therefore, AquaCrop-GIS version 2.1 was used to generate the simulation files, which were then modified and updated with the required region-specific parameters and run using AquaCrop version 6.1 (only the non-conservative parameters are presented here in Table 4.1). The parameterization of the model follows (Agoungbome et al., 2023).

The simulations require as input weather data (precipitation, maximum and minimum temperature, E_{ref} , and CO_2 concentration), soil information (soil profile, textures, and hydraulic properties of each layer), crop information (phenology, plant density, canopy cover, and max root depth) and management data (irrigation schedule, application of mulches, and water table).

4.4. RESULTS AND DISCUSSION

4.4.1. INTER-ANNUAL VARIATION OF THE ONSET APPROACHES

We explore the inter-annual yield response to varying sowing dates and evaluate the year-to-year changes of the onset to identify any particular features. Figure 4.3.a shows the inter-annual variation of crop response to the three sowing strategies during the growing season at Lat 11.5°N, Lon -3.5°W (southern Burkina Faso). Grey vertical bars represent the safe sowing window for each season estimated using AquaCrop. Red stars and black crosses show recommended sowing dates for strategies LO10mm and LO20mm, respectively. They range from the first week of May (Day 121) to the fourth week of July (Day 205), where LO10mm tends to be conservative and recommends later sowing dates (up to 20 days on average) compared to LO20mm. The safe sowing window, i.e., all dates

Table 4.1: Non-Conservative parameters adjusted (*) based on (Abedinpour et al., 2012) for 90 days maturation Maize and (Akumaga et al., 2017; Nyakudya and Stroosnijder, 2014).

Parameters description	Value	Units or Meaning	Source values
Time from sowing to maturity	90 (Fixed)	Day	97 Abedin-pour et al., 2012
Time from sowing to emergence	6	Day	6
Time from sowing to start of canopy senescence	70*	Day	72
Time from sowing to flowering	48*	Day	52 Abedin-pour et al., 2012
Duration of flowering	10	Day	10
Time from sowing to maximum rooting depth	80*	Day	-
Maximum effective rooting depth, Z	1.0	meter	1.0
Reference harvest index, HI	40	%	40 Akumaga et al., 2017
WP* reduction	54*	%	53
CCx under soil fertility stress	45*	%	40 - 77
Time to maximum canopy cover	56	Day	Automated or recommended by AquaCrop (FAO)
Building up of HI	25	Day	
Minimum effective rooting depth, Zn	0.3	meter	
Plant population	40,000	Plant/ha	
N fertilizers levels	0 (No input)	N kg/ha	Expert knowledge
Weeds management	12	% coverage	

yielding at least 90% of the maximum achievable yield, varies from as early as the first week of May to the last week of June, while cessation of the safe sowing window may be up to mid-November. The two purple horizontal lines delineate the intersection between all yearly safe sowing windows that are at least 2 weeks long, a period which is required by a smallholder farmer to sow an average farm of 2 ha.

All the safe sowing windows per season (38 out of 38 years) intersect with the Grid Safe Window (GSW), which spans from June 25th (Day 176) to July 25th (Day 206). LO10mm achieves optimal yield (more than 90% of max yield) in 28 cases and leads to yield failure ($\leq 0.2\text{ton/h}$) in only one year (1983, one of the strongest El Niño events on record (Quiroz, 1983). LO20mm identifies earlier sowing dates compared to LO10mm and, as a result, ensures optimal yield in only 10 cases, while it leads to crop failure in nearly 20% of cases (7 years out of 38), especially during the 21st century. It never fell within the GSW, thus pointing out the uncertainty of using such a strategy to determine the sowing dates. Knowing the impracticality of LO20mm due to the control period, the safe sowing window approach is more robust and easy to implement for the smallholder farmers who might not have access to climate information, especially in the context of climate-induced changes of rainfall in recent years.

In the drier part of the study area, a different timing (onset, duration, and cessation) occurs. Figure 4.3.b shows the inter-annual variation of the three sowing strategies during the growing season at a drier location, Lat 14.5°N, Lon -9.5°W (Southwest Mali). We observe a later start of the safe sowing window compared to Figure 4.3.a and a more pronounced alternation between early and late safe sowing windows, with some seasons where the safe sowing window was not identified. The safe sowing window starts as early as the first week of June, but on average occurs around the end of June. The intersection of the safe sowing windows, on the other hand, spans only the last weeks

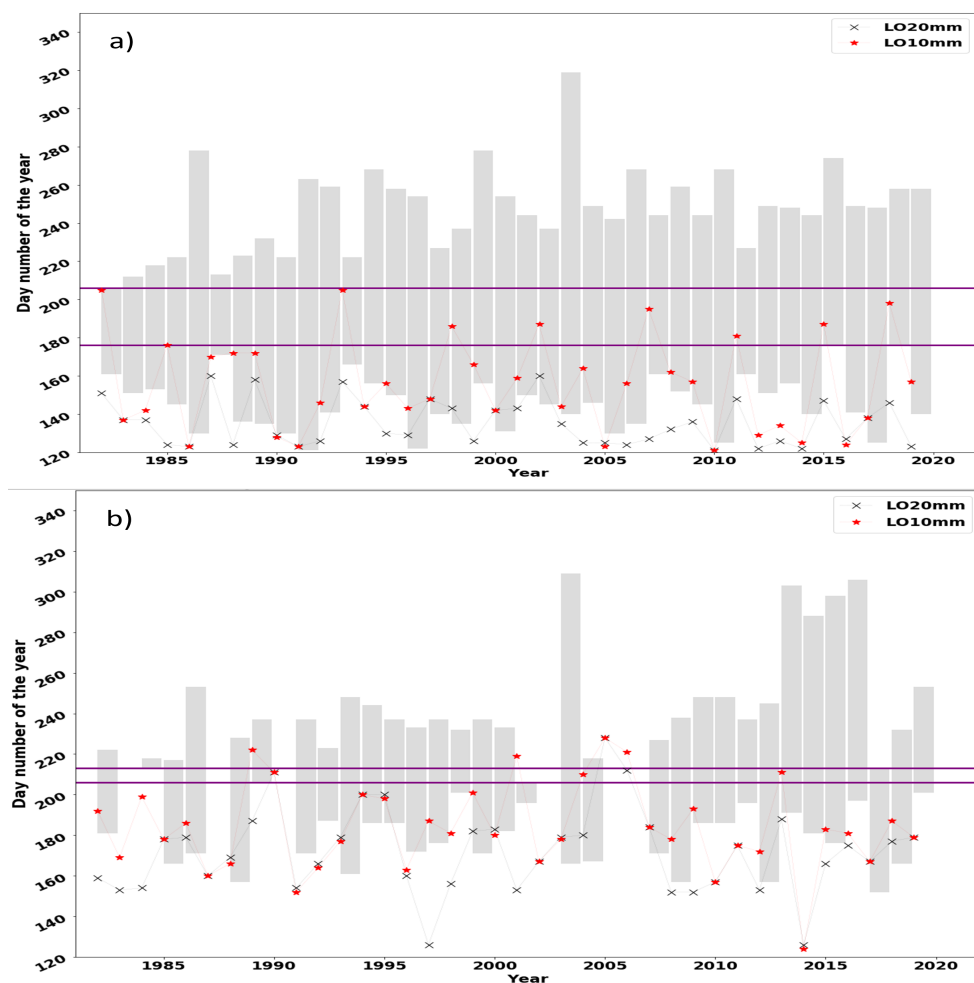


Figure 4.3: Inter-annual variation of yield response to sowing dates between 1 May and 30 November at: a) Lat 10.5°N, Lon -3.5°W, and b) Lat 14.5°N, Lon -9.5°. Grey bars represent the yearly safe sowing window. Red stars and black crosses correspond to the estimated sowing dates for sowing strategies LO10mm and LO20mm, respectively. The two purple horizontal dashed lines represent the intersection of all safe windows for all years in the dataset.

of July (Day 206 to Day 213). Regarding the rainfall-based strategies, there is an earlier estimate of the sowing dates on average around mid-June (Day 171) and early July (Day 184) for LO20mm and LO10mm strategies, respectively. However, both the LO10mm and LO20mm approaches achieve optimal yield in 20 and 13 years, respectively, out of 38 years. They estimate sowing dates that are in some cases too early, thereby leading to crop yield failure ($\leq 0.2[t/h]$), for 10 and 14 years, respectively, for LO10mm and

LO20mm over 38 years. It can also be concluded that 90-day maize may not be the best crop for these areas.

4.4.2. SAFE SOWING WINDOW ACROSS WEST AFRICA AND RISKS

Figure 4.4 shows the regional variation of the start of a safe sowing window at each grid cell. The safe sowing window refers to the intersection between yearly safe windows (90%) estimated using the crop simulation model and that are at least two weeks long. Throughout the region, the start of the safe sowing window occurs as early as the 25th of May (Day 145) to the 21st of October (Day 295). There are two axes of progression of the safe sowing window across the region. A first northward shift is observed from the savanna to the semi-arid or Sahel region. The safe window varies almost at the pace of one week per degree from the last week of June (mean = 183, std = 18 days) in the south of the savanna to late July/early August (mean = 200, std = 16 days) in the semi-arid zone. The length of the safe window also follows the latitudinal gradient and decreases from 36 days in the savanna to 15 days in the Sahel. The second shift, a northwestern shift of the safe window toward the region of the southwest of Mali and Senegal, takes place from mid-July before the safe windows occur in late July (mean = 205, std = 20 days), for an average duration of a couple of weeks.

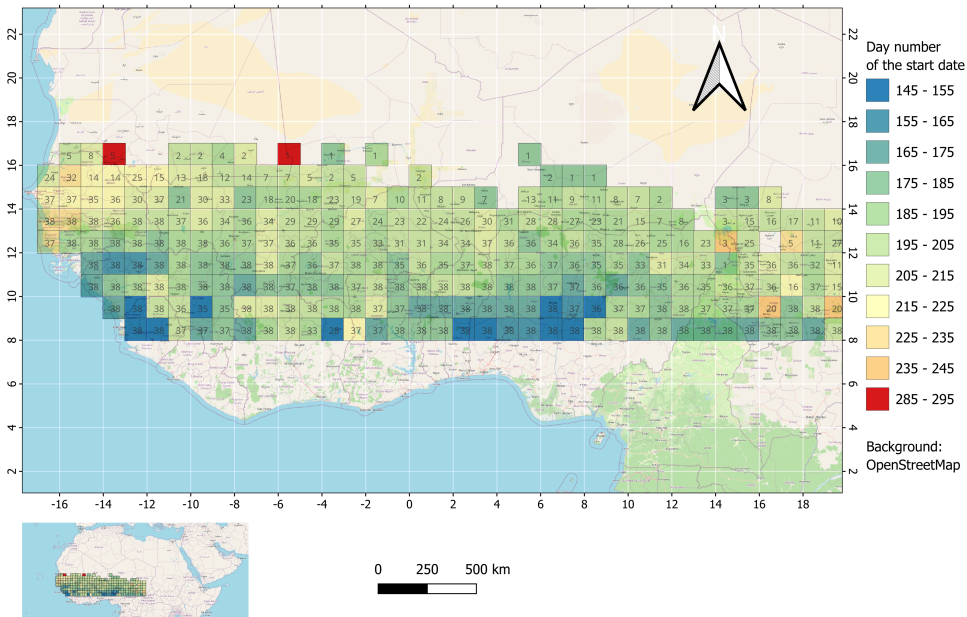


Figure 4.4: Start date of the safe window evaluated for the period 1982-2019. The average safe window represents the intersection of the yearly safe windows at each grid with the number of yearly windows considered for the intersection at the center of the grid.

Figure 4.5 displays the latitudinal migration of the sowing dates, that is, the start and

end of the safe sowing windows using the three sowing strategies. Sowing dates gradually move from around mid-May for the lower latitudes (average date Day 133 and std = 12 days for LO20mm; average date Day 144 and std = 22 days for LO10mm) at Lat 8.5°N, to later dates at higher latitudes (average date Day 206, std = 21 days for LO20mm and average date Day 220 and std = 21 days for LO10mm) at Lat 16.5°N. LO20mm and LO10mm generally follow the start of the safe sowing window for the lower latitudes (Lat 8.5°N and 9.5°N). However, sowing dates for LO20mm start about two weeks earlier relative to the start of the safe sowing window from Lat 10.5°N northward. LO10mm shows a later start (about two weeks) than the safe sowing window from Lat 12.5°N to Lat 16.5°N. The safe sowing window (mean start to mean end) is four months long at the lower latitudes (Lat 8.5°N and 9.5°N); is shortened to two months at mid-latitudes (Lat 12.5°N, 13.5°N, and 14.5°N); and to one month at the highest latitudes (Lat 15.5°N). However, the safe sowing window at Lat 16.5°N is wider/longer and, regarding the end of the window, shows a high uncertainty for potential sowing until October.

The longitudinal migration (not shown) shows limited variation in sowing dates, except for the westernmost part of the region. For LO20mm, the mean sowing dates in the central zone vary between mid and late May (Days 140 and 158), while on the western side, it occurs a month later than in the central zone and varies between Days 170 and 188. LO10mm displays a similar feature, but overall, a later start of about one week to LO20mm in each of these two zones is observed. The safe sowing window strategy shows the same behaviors as the LO20mm strategy, but with, on average, a two-week delay at both the extreme west and east sides of the region. This suggests a northward and northwestern shift of the safe sowing window from the central region of West Africa. The safe sowing window not only varies along latitudes but also shows a western shift towards the south of Mali.

These results confirm findings from climate analysis over the West African Monsoon that identify the onset of the rainy season in the central area of the region around 150 to 160 Julian days (Raj et al., 2019). It is also noticed that, despite spatial variation (geographical characteristics, vegetation, topography, landscape, human activities, etc.), the safe sowing window follows the latitudinal gradient of maximum rainfall. Safe sowing takes place after mid-June in the savanna for about one month, while it takes place between late July and early August in the semi-arid regions. Due to the northwestern migration of the safe sowing window, it is also safer to plant at the end of July or the beginning of August in the western part of the region. Such delayed sowing dates are consistent with other studies that correlate large rainfall reduction with the pre-monsoon and mature monsoon phases corresponding to April to June over the study area (Dunning et al., 2018).

4.4.3. CLIMATE EFFECTS AND RISKS ON THE ONSET OF THE RAINY SEASON BETWEEN 1982 AND 2019

To assess the effect of climate variability on the different sowing strategies, we evaluated the differences between the recent period 2011-2019 and a reference period 1982-1990. Figure 4.6 shows how LO10mm, LO20mm, and the safe sowing window have changed over time with respect to the baseline. Both LO20mm and LO10mm show a general backward shift of the sowing dates to earlier dates (1 to 2 weeks) around the center of

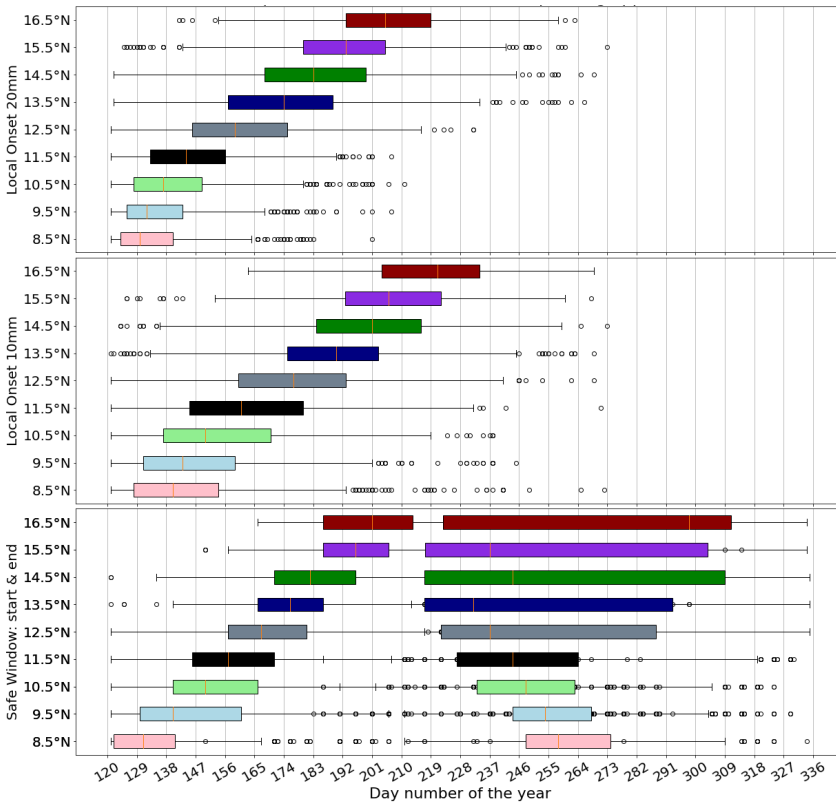


Figure 4.5: Boxplot of the Latitude-Dates of each of the different sowing approaches, for the period 1982-2019 and grid cells per latitude zone as indicated in Figure 1: a) LO20mm, b) LO10mm, c) Safe window: start and end. On the x-axis is the day number of the year, with May 1st equal to 121

the region (except for a few grid cells), while the most western and eastern areas of the region show a slight shift toward later dates (see Figure 4.6 a and b). The length of the inter-quartile range varies between 12 and 15 days for both strategies, but both show a mean value of -1.6 days and -3.3 days for LO10mm and LO20mm, respectively. Regarding the safe sowing window strategy (see Figure 4.6 c), apart from a couple of locations around the center of the area, the map shows an overall ± 20 days difference from 1982-1990 to 2011-2019. We observe, on average, a regional shift (1 to 3 weeks) of the start of the safe sowing window to later dates for most of the region. This shift to later dates is more pronounced around the northern parts of Ivory Coast, Ghana, and Togo, where farmers have indeed reported high variation and increasing dry spells during the rainy season. The extreme values (dark blue or red) represent the grids with fewer years (≤ 5) with a computed safe window per decade. The interquartile of the safe sowing window range varies between -10 and 10 days, and the average value is 0.4.

The analysis of the variation between the three decades (1991-2000, and 2001-2010,

and 2011-2019) shows, as is to be expected, a wider range of dates. For all periods, LO20mm and LO10mm show more or less the same average variation, with the interquartile range progressively increasing. These changes in recent decades could result from the uneven distribution of the start of the rainy season, which has become more unpredictable. The safe sowing window, however, shows a gradual shift to later dates, caused by devastating dry spells that have become more frequent at the beginning of the season. The intra-seasonal distribution of rainfall patterns (dry spells) could also explain such a shift. Froidurot and Diedhiou (2017) observed that the Sahel experiences an average of nearly one dry spell per season of 7 - 15 days in the middle of the rainy season. Such dry spells tend to shift the safe window to a later date to secure the maximum yield.

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Overall, these results show that the safe sowing window is shifting in the Sudanian region of West Africa to later dates in the rainy season. The two local strategies, on the contrary, show earlier sowing dates, especially in the center of the region, while the periphery of the Sudanian region shows a slight shift to later dates.

Lodoun et al. (2013) (in Burkina Faso) and later Monerie et al. (2021) (over the 21st century) noticed that the central region of West Africa will be wetter, while climate change will lead to drier conditions elsewhere. Such a trend could explain why local strategies, LO20mm and LO10mm, tend to lead to sowing dates that occur earlier in comparison to the safe sowing strategy. In addition, the more extreme rainfall events could also induce an early estimation of sowing dates by the two precipitation-based strategies. These two strategies focus on ensuring enough water at the start of the growing season and are therefore triggered by intense rain events at the start of the growing period in May. This corroborates with the study performed across Benin, Burkina, and Niger, which exhibit intense rain events that may lead to seasonal rainfall amounts close to normal but also extreme dry spells that would cause false starts and early cessation of the cropping season (Biasutti, 2019). By ignoring the subsequent dry spells after the control period (germination) that could potentially lead to a crop failure, these strategies pose a serious risk, as observed by (Agoungbome et al., 2023; Froidurot and Diedhiou, 2017). On the other hand, by computing the onset of the wet season using global climate ensemble means, Dunning et al. (2018) observed that the onset is projected to become later across most of West Africa. Although this study only considered rainfall without looking at crop growth, this method avoided isolated intense rainfall followed by dry spells at the beginning of the season (Raj et al., 2019) and therefore corroborates our results using the safe sowing window strategy.

The recommendation would still remain to consider delaying sowing to later dates as suggested by the safe sowing windows for each specific area. This result could also explain why many farmers in several locations in the region claim that the rainy season has shortened. However, since inter-annual rainfall totals have not shown high variability (Biasutti, 2019), water-saving techniques (in the field) such as rainwater harvesting would be a valid option to conserve water and soil moisture, preventing high evaporation from topsoil and increasing the soil water holding capacity. This holds especially when other considerations, such as pest avoidance or labor shortages, force the farmer to sow early.

4.5. CONCLUSIONS

We investigated different sowing strategies through crop responses to varying sowing dates for maize across the Sudanian region of West Africa. Three strategies were evaluated over 38 years to identify safe sowing windows that prevent smallholder farmers from falling into the trap of a false start of the rainy season and thus false sowing dates.

Strategies. LO20mm and LO10mm strategies identify two horizontal regions: the savanna region is situated south of Lat 11.5°, while the semi-arid zone is located north of Lat 11.5°N. In the savanna region, LO20mm and LO10mm strategies identify average sowing dates around the last week of May and the first week of June, respectively, while LO20mm estimates average sowing dates for the semi-arid zone in early July, with LO10mm two weeks later. The safe sowing window strategy, on the other hand, displays a progressive migration from the Savanna to the semi-arid region, with an average sowing window from the last week of June to mid-July, with a length of 25 days. The western area, with more variability, displays sowing dates from the last week of July to the first week of August.

Climate change. The long-term analysis highlights that the sowing dates are becoming more scattered for LO20mm, while LO10mm and the safe sowing window strategies show a relatively stable variance. Sowing dates estimated using the LO10mm and LO20mm approaches are subject to a lot of variation and tend to show an early sowing, suggesting that the region is becoming wetter. The occurrence of early extreme weather events could be an explanation for why the precipitation-based sowing strategies showed a shift to early or earlier dates. Subsequent dry spells, however, affect yields, possibly leading to yield reduction/failure. The safe sowing window approach shows a positive shift, indicating that the safe sowing window is shifting to later dates. This suggests that, with more unpredictable starts of the rainy season, sowing at later dates appears to be safer for farmers. The strategy suggests that, for the wetter areas of the Sudanian region, sowing between mid-June and mid-July is best. For the drier areas, it is safer to start sowing around the end of July to the first week of August.

The method presented here can also be used for other crops and regions, as long as the necessary auxiliary data are available. It would be interesting to expand the analysis to include future climate scenarios but, presently, climate projections for West Africa show too large a variation in magnitude and signs of future changes in rainfall (IPCC, 2023).

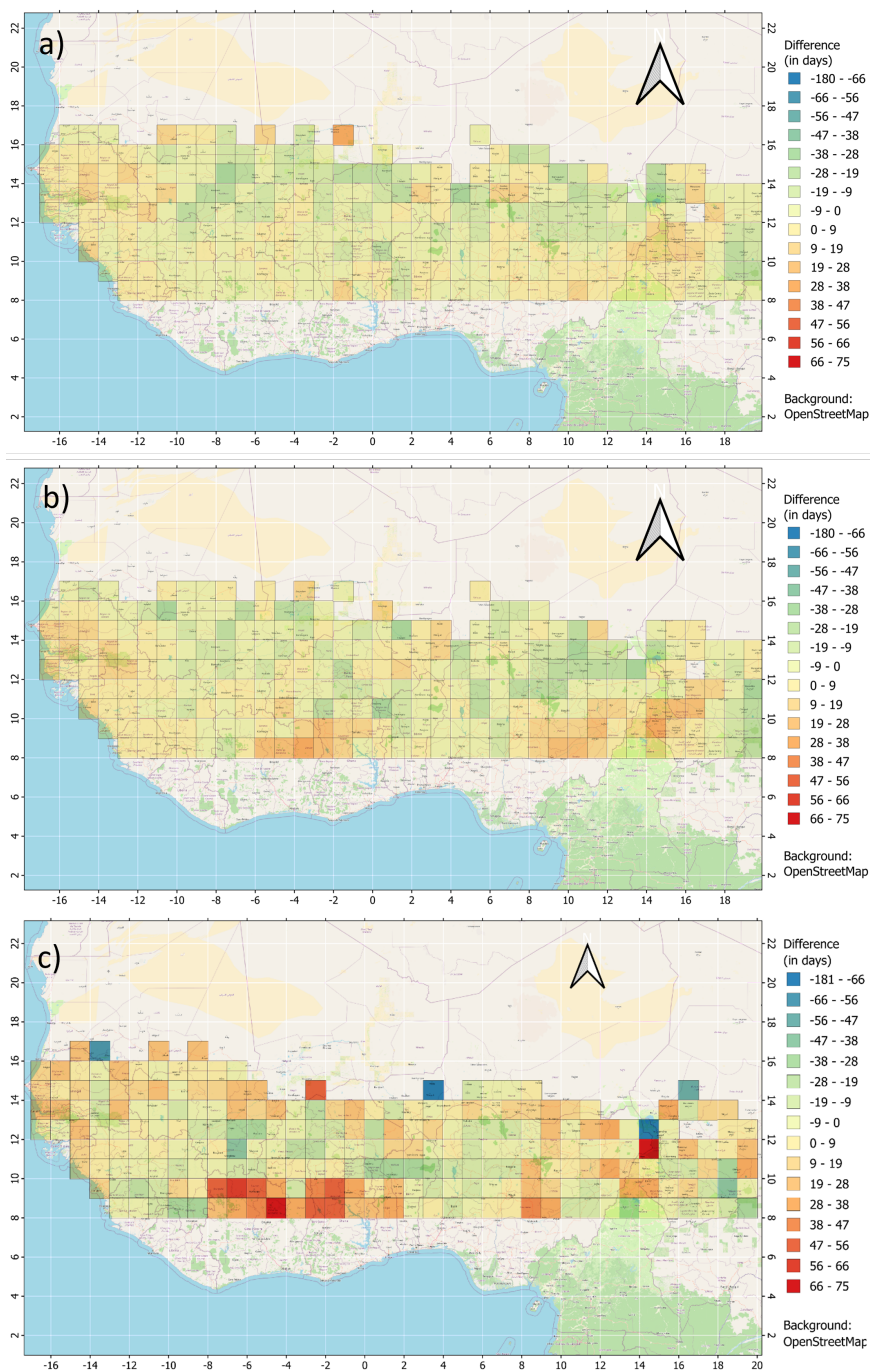


Figure 4.6: Climate effect for three sowing strategies considering the difference in recommended sowing dates and start date of the safe sowing window, between the periods 2011-2019 and 1982-1991. a) for the LO20mm sowing strategy, b) for the L10mm sowing strategy, c) for the safe window sowing strategy

5

CONCLUSION

La terre est généreuse : qui sème avec soin récolte avec abondance.

Proverbe africain

5.1. MAIN FINDINGS

This doctoral research aimed to investigate the issue of the false start of the rainy season, a phenomenon reported by farmers in the Sudanian Region of West Africa. This region is characterized by a uni-modal rainy season from May to November. Our goal was to assess the dynamics of the onset of the rainy season and crop response to different levels of water availability during the growing season.

Field visits were conducted in the Sudanian region of West Africa to evaluate farmers' views and perceptions on the issue of the false start of the rainy season. It appears that there is a common awareness among farmers in the region that the general pattern of the rainy season is changing. As noticed by nearly 50 % of the farmers interviewed, even though annual precipitation remains more or less constant, the intra-seasonal pattern of the rainy season over the past decade has changed. This observation is confirmed in research findings that show that the onset and cessation have changed: the onset has shifted to later dates, cessation of the rainy season takes place earlier (Lacombe et al., 2012; Owusu et al., 2008), higher occurrences of dry spells at the beginning and the end of the rainy season (Froidurot and Diedhiou, 2017; Kasei et al., 2010), and dry spells have become more frequent and projected to increase (Bouagila and Sushama, 2013). In the face of these changes, smallholder farmers have adopted several strategies to cope with the situation. This includes resowing the same or a different crop using short-duration seed varieties in case the first crop is lost after a period of dry spells. In northern Ghana, farmers reported that it was common to plant as early as March after the first rain, with the possibility of planting a second time during the season. However, erratic rain events followed by intermittent dry spells, also called false starts, have led them to shift the sowing until after May.

Traditionally, the sowing of cereals often takes place after the first two consecutive rainy days. In our analysis, we investigated how this sowing approach performs in the current climate context. The analysis of rainfall distribution during the growing season between May and November was performed considering 20 stations across the Sudanian region of WA. The dataset provided by TAHMO covers an average of 3 years of data, ranging from 2016 to 2020. In the literature, two approaches to defining the onset of the rainy season in the region have been proposed. The local onset LO20mm defines the onset of the rainy season as one or two consecutive rainy days accumulating at least 20 mm with no 7-day dry spell occurring during the next 30 days counted from the onset (Marteau et al., 2009). The local onset LO10mm, termed agronomical onset, accounts for both rainfall and evapotranspiration and defines the start of the growing season as an average of four consecutive rainy days exceeding 10 mm per day (Gbangou et al., 2019). To assess the adequacy of these onset strategies in the present context, crop response was evaluated for the 20 stations to identify locally safe sowing windows for smallholder farmers. AquaCrop, the FAO crop model, is used to evaluate water availability and yield response every day between 1st May and 30th November. The current approach used by farmers to define the sowing date (planting after two rain events) was shown to lead to one in four (12 out of 64 cases) complete yield failures and an average yield of 1.2 t/ha.

This is mainly due to the subsequent dry spells, from a few days up to 2 weeks on average, that occur after the first rain events at the beginning of the season and limit water availability for crop development. LO20mm and LO10mm result in higher performance,

reaching optimal yield, which is at least 90% of maximum yield in 89% and 92% of all years, respectively, averaged over all locations. However, these two approaches bring some challenges to smallholder farmers who do not have access to reliable rainfall information. Moreover, the control period of the LO20mm approach, no 7-dry-spell in 30 days following the first two rain events of 20 mm, is hardly practical. It requires monitoring for dry spells for a period of 30 days before making a decision, which may lead to sowing too late. To account for these challenges, we computed safe sowing windows that secure optimal yield (at least 90% of maximal yield) in 97% of all years at each station. The analysis revealed two main zones in the region with their respective sowing strategies: delaying the sowing date beyond the onset of the rainy season, to mid-June in the lower latitudes (south of Lon:11.5°N) and the western part of the region; and to July for the higher latitudes (north of Lon:11.5°N), ensures optimal yields in nearly all cases. Doing that enables the soil to build substantial water storage to bridge dry spells during the growing season for the years investigated, especially during sensitive stages of crop development. These outcomes of the safe sowing window strategy align very well with the local strategy LO10mm, and both help avoid the false start of the rainy season in more than 97% of cases. An important advantage of the “safe window approach” is that it is accessible for smallholders who, in most cases, do not have access to local rainfall information.

To obtain a more complete insight into the regional distribution of crop yield response to sowing dates, we analyzed the full Sudanian region of West Africa using satellite data from the Global Precipitation Climatology Centre (GPCC). The analysis of the three sowing strategies (LO20mm, LO10mm, and the safe sowing window) was conducted to assess their ability to identify safe sowing windows that prevent smallholder farmers from losing yield due to a false start of the rainy season. Using 38 years of climate data per grid cell and the crop simulation model AquaCrop-GIS, three sowing strategies (LO20mm, LO10mm, and the safe sowing window) were evaluated considering the optimal yield of at least 90% of achievable yield at the grid cell. The results confirm previous insights based on the analysis of the 20 individual stations. Two regions are identified when considering the two local onsets (LO10mm and LO20mm): the savanna region situated south of Lat:11.5°, and the semi-arid zone located north of Lat:11.5°. In the savanna region, LO20mm and LO10mm strategies identify average sowing dates around the last week of May and the first week of June, respectively, while LO20mm estimates average sowing dates for the semi-arid zone in early July, with LO10mm two weeks later. On the other hand, the safe sowing window strategy displays a progressive migration from the Savanna to the semi-arid region, with an average sowing window from the last week of June to mid-July, with a length of 25 days. The Western area, however, displays sowing dates from the last week of July to the first week of August. A comparison of these findings between a reference period (1982-1990) and the recent period (2011-2019) highlights that the sowing dates are becoming more scattered spatially for LO20mm while the safe sowing window strategies show a stable variance. Sowing dates estimated using the LO10mm and LO20mm are subject to a lot of variation and tend to show early sowing or a negative shift, suggesting that the region is becoming wetter compared to the dry reference period of the 80s. The occurrence of early extreme weather events could explain why the precipitation-based sowing strategies showed a shift to earlier dates. Subse-

quent dry spells however, affect yields, possibly leading to yield reduction/failure. The safe sowing window strategy shows a positive shift, indicating that the safe sowing window is shifting to later dates.

5.2. IMPLICATIONS FOR FARMERS AND EXTENSION AGENTS

The analysis highlights the need for precautions due to erratic rainfall at the beginning of the season. With more unpredictable starts of the rainy seasons, sowing at later dates appears to be safer for farmers. The safe sowing window strategy recommends that for the wetter areas of the Sudanian region, sowing between mid-June and mid-July is best. For the drier areas, it is safer to start sowing around the end of July to the first week of August.

In the context where climate services are not possible or the structure is not yet available or in place, we recommend using the strategy provided in this dissertation at the local and regional levels. They can ensure at least 90% of maximal yield. However, we recommend that the guidelines or safe windows be updated following a similar methodology, as long as the climate conditions keep changing.

With a strong diversity of people and communities in the Sudanian region of West Africa, speaking different languages with various literacy levels, the question of what format of climate services is relevant. Several options arose throughout the discussion with the smallholder farmers, such as voice notes on mobile phones, and short messages in local languages on local radio/TV stations. Moreover, using the system of extension agents in the context of West Africa (existing in Ghana and Benin) can play an important role. They are already available at the service of the state research agencies and local agricultural agencies, and act as the intermediary/relay with the local farmers in specific areas. Having the necessary education level, the extension agents could update the sowing recommendations every season with newly available climate data and convey the relevant information to the farmers at the local level. The information could range from sowing dates to the varieties suitable for that season.

5.3. RECOMMENDATION FOR FUTURE RESEARCH

The analysis in this thesis focused on maize, a major staple crop in WA. We recommend that similar studies be conducted for crops with different growing cycles, hence responding differently to rainfall variability during the growing seasons. For instance, we would confidently recommend that the methodology presented in this dissertation be used for other cereal crops and other regions to assess how they adapt to changing climate conditions, provided that the necessary auxiliary data are available for the evaluation. Knowing that future climate conditions and dynamics in West Africa will likely vary, it would be interesting to expand the analysis to include future climate scenarios. This will enable decision-makers to take preventive measures and the adoption of adaptive innovations. However, such an exercise is difficult since there is a huge gap in the availability of historical climate data (van de Giesen et al., 2014a), and climate projections for the region show enormous inter-model variability. Despite innovative initiatives ranging from low-cost weather stations to combining remote sensing with citizen science, current remote sensing data, especially rainfall satellite products, are still coarse, and less reliable

in reproducing intra-seasonal variations (performance in estimating and reproducing rainfall amounts; detection capabilities of consecutive dry/wet spells), and show large errors (Dembele and Zwart, 2016). Future projections are even more dramatic. Projections over the West African region show little consensus on the direction and magnitude of potential changes in rainfall (IPCC, 2012; Sultan and Gaetani, 2016; Sylla et al., 2016).

The gap in weather observation needs to be reduced, and steps toward improving climate projections for West Africa to support science-led adaptation measures (IPCC, 2023). Whether this is done through public or private structures, access to improved rainfall information for the scientific community needs to be facilitated to support the dissemination of science-based guidelines.

To enhance our understanding of the complex system of climate-crop-soil, efforts should be directed not only to the laboratory but also to large-scale field studies to understand the interactions of each component, supported by possible scenarios (under high/low CO_2 level, new varieties of crop species). A detailed understanding of water, heat, and nutrient stresses on crop growth, as well as the feedback loop between the aboveground crop and the root system, is an aspect that can help optimize food production and reduce the pressure on available resources.

Reducing the gap of food insecurity implies improving crop production. Some areas to investigate regarding the farming system in West Africa could be the density of sowing, which we took to be four plants per square meter. According to the interviews with farmers who sow at higher density, multiplying this by four would guarantee high productivity but also pose the problem of soil fertility and nutrients, and water availability for crop development (Abdul Rahman et al., 2018; Desmae et al., 2022; Sultan and Gaetani, 2016). With limited finances, local practices should be studied together with possible improvements. Improved and resistant seed varieties should be adopted in the region, provided that they are sustainable. However, farmers have reported how dependent they become on using these improved seeds and how the business model behind them does not work in the long term.

Rainwater harvesting techniques have proven results not only in bringing additional water to crop development to face challenging dry spells but also in providing extra nutrients to the soil (Ramthun and Mishra, 2022; Wiersma, 2023). Special attention should also be given to increasing soil water holding capacity by exploring measures that enhance soil biosphere development and fertility level. As we face an urgent call for optimal water use, rainwater harvesting techniques at the field scale, as well as large scale, need further exploration to understand the benefits they bring to crops. Its general implementation in adaptive measures of smart agriculture should be done in semi-arid, arid, and stress-prone regions like the Sudanian region of West Africa.

5.4. CRITICAL REFLECTION ON THE APPROACH AND SOURCES OF UNCERTAINTY

This study explores the use of the FAO model AquaCrop to assess crop response to varying climate conditions and management scenarios in the Sudanian region of West Africa, drawing upon datasets such as TAHMO and GPCC. Although the findings offer useful information, it is crucial to acknowledge the inherent limitations and sources of uncer-

tainty of the approach.

5.4.1. LIMITATIONS OF THE TAHMO DATASET

One major limitation of our approach relates to the climate datasets used for the analysis. The TAHMO dataset, for example, plays a critical role in filling weather data gaps across sub-Saharan Africa. However, for the study region, TAHMO data, while valuable for increasing spatial coverage in this data-scarce region, includes only a short period of observational data, just three consecutive years for most stations.

This limited temporal span constrains the robustness of climate-related inferences, as it fails to capture the interannual variability and long-term climate trends characteristic of the West African Savanna (Liebmann et al., 2012; Sylla et al., 2015). Consequently, conclusions drawn from model simulations based on this dataset must be interpreted with caution. Furthermore, despite the high-frequency and standardized nature of TAHMO sensors, independent evaluations of the network's data quality have highlighted challenges related to calibration consistency and sensor maintenance (van de Giesen et al., 2014b). In areas where station-level maintenance is constrained, data gaps or sensor drift may introduce additional uncertainty. The short time series exacerbates the risk of bias, especially when extreme years dominate the dataset. Nevertheless, the dataset has also been used as the ground truth to improve satellite-based remote sensing products, which afterwards showed high performances (Le Coz et al., 2019).

This short timeframe limitation is, however, addressed in this research at [chapter 4](#) when we use the GPCC dataset (1982-2019) to evaluate the long-term variability.

5.4.2. MODEL SUITABILITY AND COMPARATIVE LIMITATIONS

Several studies have raised concerns about AquaCrop's performance in semi-arid and drought-prone environments. In particular, AquaCrop may overestimate biomass recovery following prolonged water stress events due to its simplified physiological assumptions (Foster et al., 2017). This issue is critical in the Savanna zone, where rainfall is both seasonal and highly variable. Such tendencies could lead to optimistic yield projections under stress scenarios.

Moreover, while AquaCrop was chosen for its balance of simplicity and empirical robustness, its strengths include its focus on simulating the crop response to water stress, a critical feature for studies in semi-arid climates. Although alternative models may better capture complex physiological and nutrient interactions, they often require input data and calibration resources that were unavailable in this study. Consequently, while AquaCrop remains a pragmatic choice, it is important to qualify its limitations in modeling nuanced crop responses to environmental stressors. A comparative analysis of model strengths and weaknesses could enrich future assessments.

5.4.3. MODEL CALIBRATION AND VALIDATION CHALLENGES

Although the AquaCrop model is widely recognized for its applicability in semi-arid regions and data-scarce contexts, due to its relatively modest data requirements (Steduto et al., 2009), effective calibration and validation of the model typically demand site-specific biophysical data, such as time-series yield measurements, soil profiles, and field-level management practices (Raes et al., 2018). In this study, such data were sparse. As

a result, calibration had to rely on a combination of literature-derived parameters and local expert input. This inevitably introduces parameter uncertainty and limits the precision of absolute yield predictions.

To partially address this gap, farmer interviews were conducted to gather information on observed yields, stress periods, and cropping practices, and these data were used to contextualize and partially validate simulation outputs. While valuable for contextual understanding, these data are retrospective, self-reported, and sometimes imprecise, serving better as a qualitative cross-check than as a robust quantitative validation dataset. While these insights added valuable local knowledge, they cannot substitute for quantitative calibration based on controlled field trials. Consequently, the reliability of the simulated yields, particularly the absolute values, may be accompanied by significant uncertainty. This limits the capacity to use AquaCrop in this context for precise predictions, although it remains valuable for scenario comparison and relative sensitivity analysis, especially for water stress.

5.4.4. IMPLICATIONS FOR RECOMMENDATIONS AND POLICY RELEVANCE

Given the limitations of input data, calibration challenges, and model-inherent simplifications, the results of this study should be interpreted with caution, and the recommendations viewed as indicative rather than prescriptive based on existing assumptions and available data. The study's comparative findings between different sowing approaches remain valuable for identifying general trends (e.g., safe sowing windows for specific regions), but quantitative conclusions about yield levels or climate impact magnitudes should be interpreted cautiously. Further empirical studies, expanded datasets, and enhanced model calibration efforts will be necessary before implementing large-scale recommendations based on this research.

Future work should prioritize longer-term data collection, model calibration under local conditions, and integration of multiple modelling frameworks to triangulate findings. This would help strengthen the robustness and policy relevance of conclusions drawn in similarly data-scarce regions.

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David

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2022	Finalist and Public vote for Best Pitch, TU Delft Impact Context
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LIST OF PUBLICATIONS

7. **Agoungbome, S.M.D.**; ten Veldhuis, M.-C.; van de Giesen, N.; 2024. *Safe Sowing Windows for Smallholder Farmers in West Africa in the Context of Climate Variability*. [Climate](#) 2024, 12, 44.
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3. **Agoungbome, S.M.D.**; Gbenontin E.; Thiam M.; 2020. *Mangroves Under Demographic Pressure and Salt Production Threats in the Municipality of Ouidah (Benin)*.[InterSol](#) 2020, vol 321. Springer.
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