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Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management in southern Mali

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ABSTRACT

Production of cereals (maize, sorghum, millet) in southern Mali is challenged by several hazards that affect yield and yield variability. The research aims to inform decision making towards effective risk management by quantifying cereal yield losses at field level due to production hazards under different management strategies. Five hazards relevant for farmers were analysed: late onset of rains, insufficient total rainfall, dry spells, low fertiliser quality and sudden lack of labour. The frequency and impact on yield of these hazards were assessed by combining a long term weather database (1965–2019) with outputs of the DSSAT crop model (baseline and optimised variety, fertiliser rates and sowing dates), and visualised in a risk matrix. The prevalence of the weather hazards was common, with all of them occurring at least once every five years. Frequency of non-weather hazards were perceived to occur once every five years (labour hazards) and once every ten years (fertiliser hazards). Under baseline conditions maize (3.39 t / ha) outperformed sorghum (1.74 t / ha) and millet (1.33 t / ha), except in cases of fertiliser hazard when sorghum yielded more than maize. Maize responded relatively well to N application, and sorghum performed relatively well without N application. The benefit of millet resided in low yield variability, and lower sensitivity to the weather hazards. Changing management to optimise yields generally involved early sowing (22 days, 2 days and 27 days after onset for maize, sorghum and millet), increased N applications (66 kg N / ha, 27 kg N / ha and 111 kg N / ha for maize, sorghum and millet), and using short duration varieties. For millet the long duration variety was more beneficial. For maize there was opportunity to increase the yield without affecting the risk of yield loss, while for sorghum there was a synergy and for millet a trade-off between yield and risk. The different interactions between hazards and management for the three cereals stress the importance of maintaining farm diversity, as well as operational farm flexibility to respond to production risks.

1. Introduction

Smallholder farmers in West Africa are challenged by a diversity of agricultural risks for both food production and income (Huet et al., 2020; Komarek et al., 2020), with climate change likely to increase the hazards (Campbell et al., 2016; IPCC, 2012). The risk for farmers depends on both the impact of a hazard and the frequency with which it occurs (World Bank, 2016). In such volatile circumstances, much research focuses on how farmers can build resilience because they are vulnerable to hazards and the resulting production variability leads to food insecurity and low income (Kloos et al., 2015; Bullock et al., 2017; Meuwissen et al., 2019). Further, climate hazards are linked to migration and conflicts, although this relationship is complex and remains debated (Benjaminsen et al., 2012; Mach et al., 2019). By understanding the extent of risks and identifying possible mitigation measures, research can generate knowledge needed to build farmers' resilience. Such risk information helps farmers to fine-tune farm management and helps policy makers to define policies to mitigate risk (Descheemaeker et al., 2016).

In Sudano-Sahelian farming systems, cereals play a central role as staple crops, contributing to food self-sufficiency, as well as generating income (Falconnier et al., 2015). Current cereal yields remain far below

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the water limited potential (ten Berge et al., 2019; Adam et al., 2020). In addition, yields vary strongly between fields, farmers, and years (Falconnier et al., 2016). For example, in the cotton zone of Mali farmers obtain average maize (*Zea mays* L.) yields of 2 t / ha, while 5 t / ha is obtained by some in good years (Traore et al., 2014; Falconnier et al., 2016). Sorghum (*Sorghum bicolor* (L.) Moench) and millet (*Pennisetum glaucum* (L.) R.Br.) yield less: on average 0.9 and 0.8 t / ha with maxima of around 3 and 2 t / ha respectively (Traore et al., 2014; Falconnier et al., 2016; Adam et al., 2020). Crop yield variability is partly induced by incidences of hazards, including climate hazards (Aune and Bationo, 2008; Schmitt Olabisi et al., 2017; Akumaga and Tarhule, 2018), pest attacks (Schlecht et al., 2006) and farmer or animal illness (Huet et al., 2020; Segnon et al., 2020).

Farmers' perceptions and attitudes towards such hazards guide crop management decisions to prioritise either maximising or stabilising yield (Descheemaeker et al., 2016; Khumairoh et al., 2018). Furthermore, smallholder farmers apply several measures to deal with risks in semi-arid regions. For example, farmers might target or spread sowing dates strategically (Milgroom and Giller, 2013; Traore et al., 2015), plan fertiliser use carefully (Piha, 1993; Freduah et al., 2019; Adam et al., 2020), or use diverse varieties that have a different response to stress (Frison et al., 2011; Adam et al., 2018). Many risk management decisions are operational or tactical, which means they are planned and implemented on a short- to medium-term horizon going from a couple of days (e.g. adapting fertiliser application, harvest timing, pest management) to a couple of months (e.g. land allocation, selection of crop cultivars, planning of fertiliser application) (Nissan et al., 2019). The long-term strategic decisions that farmers implement are diversification (Mubaya and Mafongoya, 2016) and maintaining flexibility so that they are prepared for, and can adapt to occurrences of hazards that influence crop production (van Noordwijk et al., 1994; Brouwer et al., 2007). However, the effect of these management decisions in the face of hazards, both in terms of average yields as yield variability, is often not well quantified for West-African cropping systems.

Crop growth models, combined with long-term weather data, are powerful tools to assess crop production risks (van Noordwijk et al., 1994; Ewert et al., 2015). In West-Africa, crop models have been extensively used to understand the response to climate change (Traore et al., 2017; Amouzou et al., 2019; Sultan et al., 2019; Defrance et al., 2020). Less literature describes the effects of current seasonal variability (e.g. Fosu-Mensah et al., 2012) or non-climate related hazards. Yet, understanding how farmers can deal with current variability helps to design risk management strategies for a future affected by climate change (Cooper et al., 2008). When crop models are used to assess risks they are also often focused on a single crop, and on a limited set of management practices without including their interaction (Ewert et al., 2015), or on the impact without taking into account the frequency of the hazard (Challinor et al., 2018). Of the three cereals commonly grown in the drylands of West Africa (maize, sorghum, millet), millet is less investigated through crop models (e.g. Akponikpè et al., 2010).

In this paper we address the above knowledge gaps by using a crop model to explore impacts on three major cereal crops in southern Mali, a region prone to risks as is much of semi-arid West-Africa. The research aims to inform decision making towards effective risk management by quantifying cereal crop yield losses at field level due to the interactions of different production hazards under varied management strategies. Firstly, we assess the frequency of the most important hazards in the region. These hazards were identified and defined by farmers; a starting point deemed crucial by Challinor et al. (2018) for a meaningful risk assessment. Secondly, we quantify the impact of the hazards on crop yields and explore how current and optimised management practices influence yield and yield stability. Additionally, frequency and impact of the hazards are combined in a risk matrix for both current and optimal management. Finally, we explore the interaction effects of management factors (variety, sowing dates, fertiliser rates and soil type) on yield to understand where the baseline and optimal management are situated within the decision space available to farmers.

2. Methods

2.1. Site description

Our study area comprises the rural area around Koutiala (12°23′ N, 5°27′ W) in the cotton zone of southern Mali, located in the semi-arid, Sudano-Sahelian region. With Lixisols as the dominant soil type (FAO, 2006), farmers recognise three subgroups (Falconnier et al., 2016): sandy soils were most common on farmers' fields, occupying 65 % of the cultivated area, followed by black (25 %) and gravelly soils (10 %). Agriculture is rainfed during a unimodal rainy season between May and October.

Farmers aim to cultivate sufficient maize, millet and sorghum to feed their households (Kanté, 2001). Income is generated by cultivating cotton and by selling their surplus of cereals, especially maize (Bosma et al., 1999; Losch et al., 2012; Falconnier et al., 2015). On average farmers cultivated 12.6 ha and targetted 8.6 ha to cereal production, of which 27 % was maize, 30 % sorghum and 43 % millet. Crop-livestock interaction is important in this farming system with crops providing feed and livestock providing manure, as well as draught power and cash (Kanté, 2001; Van Dijk et al., 2004).

2.2. Hazard identification and general approach

Huet et al. (2020) described the hazards that farmers perceived important. Here we consider a subset of these hazards that affect cereal production (Table 1). The risk of these hazards is quantified by the simulated impact on cereal yield and the frequency with which they occur.

The frequency of weather hazards was analysed based on long-term weather data (see Section 2.3). For the additional hazards, such as sickness of animals or labour force, and bad quality of fertiliser, the frequency was estimated by farmers as described in Huet et al. (2020). The crop response to hazards was evaluated by comparing simulated yields under hazardous and non-hazardous conditions. The non-weather hazards were reflected by changes in crop management practices (Table 1) which can be captured by a crop model.

2.3. Frequency of weather hazards

During four focus group discussions, farmers defined at what point they judged a certain weather situation to be problematic (Table 2). For example, an onset of the rainy season after the 1st of June was deemed late in one focus group (i.e. moderate hazard level), while the other groups benchmarked the 15th of June (i.e. strong hazard level). Dry spells longer than one week in the early stages of the rainy season and total rainfall of less than 750 mm / year were also seen as problematic.

Table 1
The hazards farmers ranked as having strongest impact on cereal production according to Huet et al. (2020).

Hazard	Rank	Risk assessment	Hazard type
Sickness labour force	1	Evaluate impact of late sowing because of labour shortage	Non-weather
Sickness animals	2	Evaluate impact of late sowing because of labour shortage	Non-weather
Late onset	3	Evaluate frequency and impact of late start rains	Weather
Bad rainfall distribution	4	Evaluate frequency and impact of dry spells during the growing season	Weather
Lack of rain	5	Evaluate frequency and impact of low total yearly rainfall	Weather
Bad quality fertiliser	8	Evaluate impact of smaller N application rate (set to 0 kg N / ha)	Non-weather

Table 2
Farmers' definition of weather hazards, complemented with information from literature and definition of thresholds.

Hazard	Farmers' definition of hazard	Threshold	Level of hazard	Rainfall-based parameters from literature used to calculate threshold	Reference
Late onset rain	After 1 June (some farmers mentioned 15th June)	1st June	Moderate	First day in sowing window when > 20 mm of rainfall is received cumulatively within 7 consecutive days	Wolf et al. (2015); GYGA (2020)
		15th June	Strong		
Uneven distribution of rain	Dry spells are problematic from 1 to 2 weeks without rain. In the middle of the rainy season, dry spells can last up to 3 weeks without doing much harm.	1–3 moderate dry spells (7–14 days) in first 60 days after onset	Moderate	The length of a dry spell is the number of consecutive dry days between two rainy days. A day with a rainfall amount less than 1 mm is considered a dry day.	Sivakumar (1992); Salack et al. (2011); Boansi et al. (2019)
		> 3 moderate dry spells in first 60 days after onset	Strong		
		Long dry spell (>14 days) in first 90 days after onset	Strong		
Low total rain	< 750–800 mm	750 mm	Moderate	Annual rainfall	
		650 mm	Strong	Annual rainfall below limit of Sudano-Sahelian agro-ecological zone	

Definitions for onset and dry spells obtained from literature (Table 2) were used to complement farmers' definitions when setting thresholds for different hazard levels.

Long term daily observed weather data (1965–2019) from the nearby N'Tarla research station (12°35' N, 5°42' W) (Traore et al., 2013) were used to calculate the frequency of weather hazards using the above definitions. Recent (2012–2019) solar radiation data was extracted from the Prediction of Worldwide Energy Resource (POWER) dataset (NASA, power.larc.nasa.gov, accessed 24/09/2020), often used in crop growth simulations (Van Wart et al., 2015; Joseph et al., 2020).

2.4. *DSSAT crop model for estimating yields*

2.4.1. *General settings*

Crop growth and development was simulated with the Cropping System Model (CSM) (Jones et al., 2003) of the Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (Hoogenboom et al., 2019) using the CERES model components (Jones and Kiniry, 1986; Ritchie et al., 1998). Crop growth is simulated on a daily time step based on cultivar genetic coefficients, crop management, weather conditions, and soil water and nutrient dynamics, with a re-initiation of the model each year. N and P are the most limiting nutrients in the region (Fosu-Mensah and Mensah, 2016), but as the effects of P on crop growth are only included in DSSAT for CERES-maize (Dzotsi et al., 2010) and CERES-sorghum (Adam et al., 2018), we focused only on N. The CENTURY model (Parton et al., 1988, 1994) was used to simulate soil organic matter dynamics (Gijsman et al., 2002; Jones et al., 2003). For other soil-plant-atmosphere calculation methods, we used the default DSSAT methods. We indicated sowing dates manually (at five-day intervals within a sowing window of 10th of May to the 1st of August), but harvesting was simulated automatically at crop maturity. The sowing window was set with a minimum starting date to exclude false starts of the rainy season and to reflect general farmers' practices.

The DSSAT soil and cultivar parameters were obtained from peer-reviewed publications that parameterised and evaluated the soils and cultivars in semi-arid regions of West-Africa, as specified below. Three soil subgroups were considered for the area: sandy (baseline), gravelly and black soils. The DSSAT soil profiles (*. SOL) were constructed with information from soil analysis described in Falconnier et al. (2016) (Table S1). The SLPF parameter (soil-limited photosynthesis factor) was set to 0.7, similar to on-station soils in Mali (Singh et al., 2014), and confirmed by comparing simulated and observed yields from a three-year cereal trial in the nearby N'Tarla research station (Traore et al., 2014). With a high content of sand, all soils were considered well drained with a respective drainage rate (SLDR) of 0.6 fraction / day (Gijsman et al., 2007). Crop residues were not taken into account, as farmers' practice is to remove a large proportion of them for animal feed or composting. The simulations were initiated on the first of April of each year, when the water content was considered to be at wilting point for all soil profile layers. For the sandy and black soils, mineral N at the start of simulation was estimated at 20.8 kg N / ha (Falconnier et al., 2020). The initial mineral N content of the more shallow, gravelly soils was set at half this content, being 10 kg N / ha.

For each of the cereals, we compared a baseline variety considered as an intermediate crop cycle that is regularly used by farmers in Koutiala, with a short and long duration variety. If no parameters were available for varieties grown by farmers, we used parameters for similar varieties (Table S2). An overview of general cultivar characteristics is provided in Table S3. For maize, parameters of the baseline Obatampa variety and the short duration TZEEY-SRBC5 variety were obtained from Freduah et al. (2019) while parameters of the long duration SUWAN 1-SR were used from Falconnier et al. (2020). The sorghum variety CSM335 was used as baseline (Adam et al., 2018; Faye et al., 2018b). CSM 63E is a Malian variety that has a shorter maturity cycle (100 days), while IS15–401 generally has a longer cycle (110–160 days). For all sorghum varieties, we used the DSSAT parameters of Adam et al. (2018). Parameters for millet varieties grown in West Africa are scarce. CIVT is a variety that is best described and parameterised, often for studies in Niger, and therefore used as baseline variety in our study. Singh et al. (2017) defined parameters for CIVT, as well as a hypothetical short duration CIVT variant (10 % shorter) and a hypothetical longer duration CIVT variant (10 % longer). Planting density was set at 50,000 plants per ha for sorghum and millet, and at 62,500 plants for maize (Traore et al., 2014).

2.4.2. *Cereal management*

DSSAT was run for a wide range of factor level combinations for varieties (short, intermediate and long duration), sowing dates (18 fixed sowing dates between 10th May and 1st August), soil types (sandy, black and gravelly), and fertiliser (N) rates between zero and 200 kg N / ha given in split-application (Table S4) to understand how these management factors interacted in affecting yield, yield variability and yield loss due to hazards. Within this range of management settings in DSSAT we defined specific management combinations that reflect (1) farmers' practice as baseline management, (2) management leading to optimal yields and (3) management reflecting non-weather hazards.

Baseline cereal management practices were derived from detailed farm management surveys conducted with 25 farmers in 2018 and 2019 (Dissa A., personal communication). The baseline N application was rounded to 50 kg N / ha for maize, 10 kg N / ha for sorghum and 15 kg N / ha for millet. In 2018 and 2019, on average farmers planted millet first on the 9th of June, followed by maize on the 24th or June, and sorghum on the 1st of July. These sowing dates occurred 23, 36 and 39 days after the onset of the rainy season respectively, confirming that farmers first target sowing of cotton (Soumaré, 2008). For the baseline simulations, each year's sowing date was based on the above average number of days after the onset of the rainy season.

Optimal management was defined for a single factor under otherwise baseline conditions and for all factor combinations, whereby the method for calculating the optimal level differed per management factor (fertiliser, sowing date, variety), as explained below. The optimal sowing date of each year was defined as the sowing date relative to the onset of the rainy season (i.e. number of days after onset) that resulted in the largest yield. The average of these number of days was regarded as the period between onset and yearly optimal sowing date. Conversely, the least optimal sowing date was the average sowing date resulting in the smallest grain yield. The optimal variety was the variety that most often resulted in the largest yield over the 55 years. The optimal N rate was the average of the rates that resulted in the maximum yield per year with a positive return on fertiliser investment (Getnet, 2016). Applying one extra unit of N obtained from subsidised fertiliser cost 4.87 USD PPP / kg N, while the grain price was 0.50, 0.52 and 0.66 USD PPP / kg for selling maize, sorghum and millet respectively. Grain prices were averaged from monthly prices in 2016 (OMA, 2016) and fertiliser prices from a market analysis (Dissa A., personal communication; World Bank, 2020). The optimal management for the combined factors was defined by first identifying the variety that most often gave the largest yield, and then determining the combination of sowing date and N rate that gave the largest yield with a positive return on investment.

Hazards not related to weather events (Table 1) were reflected in a change in crop management within DSSAT. Household members or draught animals falling sick at the beginning of the rainy season affects land preparation and sowing of crops. We assumed that this labour shortage delays the sowing date by two weeks. Bad quality of fertiliser was reflected by setting the mineral N application rate to zero.

2.5. *Impact of hazards and crop response to management*

We compared crop yields in years with and without weather hazards under baseline and optimal management. For the non-weather hazards, baseline yields for all years were compared with yields under adjusted management. The impact of a hazard was indicated by the percentage yield loss. For each of the cereals, this percentage yield loss (YL) is calculated as follows:

$$YL = \frac{\left(\sum_{1}^{n} Y_{man,NH_i} \Big/ n - \sum_{1}^{m} Y_{man,H_i} \Big/ m \right)}{\sum_{1}^{n} Y_{man,NH_i} \Big/ n} \times 100$$

where,

- *man*: Type of crop management (baseline, optimal)
- *Y*: Cereal yield (kg / ha)
- *NH*: Years with no hazard, and management not affected by hazard *i*
- *H*: Years with hazard, or management affected by hazard *i*
- *i*: Type of hazard (late onset, low total rainfall, fertiliser, labour hazard)
- *n*: Number of years without hazard *i* (in case of the fertiliser or sowing hazard, $n = 55$ because they are independent of the weather conditions)
- *m*: Number of years with hazard *i* (in case of the fertiliser or labour hazard, m=55 because they are independent of the weather conditions)

We also assessed the effects of management practices and their interactions on yields and on the stability of yields over the 55 years. The stability of yields was determined by the coefficient of variation. Analysing how management factors interact helps to understand how baseline and optimal management relate to each other within the decision space that farmers have. When focussing on certain management interactions, the other management factors were held at baseline level.

2.6. *Risk assessment*

Risk is a combination of the frequency and impact of hazards, which was visualised in a two-dimensional risk matrix, with frequency following the scale of the World Bank, 2016 on the x-axis and impact as the percentage yield loss on the y-axis. A high frequency in combination with a high impact, indicated a high risk. The frequency of two hazards occurring simultaneously was calculated by multiplying the probability related to each individual hazard. For example, if the first hazard occurs one out of two years, and the second hazard one out of three years, we assume the combination occurs once every six years. In the case of two simultaneous weather hazards, the frequency was deduced from the weather data. The risk matrix was constructed for baseline and for optimal management.

3. Results

3.1. *Frequency of weather hazards*

Long-term weather data over 55 years gave insight into the likelihood of occurrence of climatic hazards that were important to farmers: a small total rainfall amount, late onset of the rains, and dry spells. The mean total annual rainfall was 863 mm, ranging from 482 mm to 1249 mm. Total rainfall was less than 750 mm in 35 % of the years (Fig. 1a). Nevertheless, in five out of these 19 years the rainfall dropped less than 10 mm below the 750 mm threshold. In 7 % of the years a strong hazard with less than 650 mm occurred.

The onset of the rainy season was on average on the 23rd of May and ranged from the 10th of May (in nine years), to the 1st of July (Fig. 1b). On average, the rainy season lasted 168 days and ended on the 7th of November, with a range between the 20th of September and the 29th of November. A moderately late onset of the rainy season, after the 1st of June, occurred in 18 % of years, whereas the rains started after the 15th of June in 7 % of the years (strong hazard). Moderately late onset of the rainy season combined with a moderately low total rainfall happened in 13 % of the years.

On average a rainy season counted 116 dry days and 52 rainy days (Fig. 2). Dry spells of at least a week within the first month after onset occurred in 71 % of years, and in 7 % of years these lasted longer than 14 days. After this first 30-day period after onset, dry spells tended to be shorter. Overall, a quarter of the years did not exhibit any hazardous dry spells.

3.2. *Crop response to hazards under farmers' practice*

Maize, which received more N under baseline management, yielded more than sorghum and millet overall, with an average yield of 3.39 t / ha, 1.74 t / ha, and 1.33 t / ha, respectively. When comparing yields under baseline management in years with and without a weather hazard (Fig. 3), sorghum and maize performed worse in years with low total rainfall, while millet yields were more robust and did not exhibit such variation (Fig. 3a). In years with a late onset of the growing season, all three cereals yielded less, although for millet only in years with a strong hazard (Fig. 3b). The presence of dry spells had a limited effect on cereal yields (Fig. 3c). The small positive tendency in yields with dry spells could be related to a confounding effect with the other two weather characteristics analysed. Years with a hazardous dry spell had an earlier average onset of the rainy season (18th May) and a higher mean total rainfall (874 mm) compared to years without a hazardous dry spell (30th May and 830 mm). Additionally, cereals are sown relatively late under farmers' practices compared with the onset, which allows these

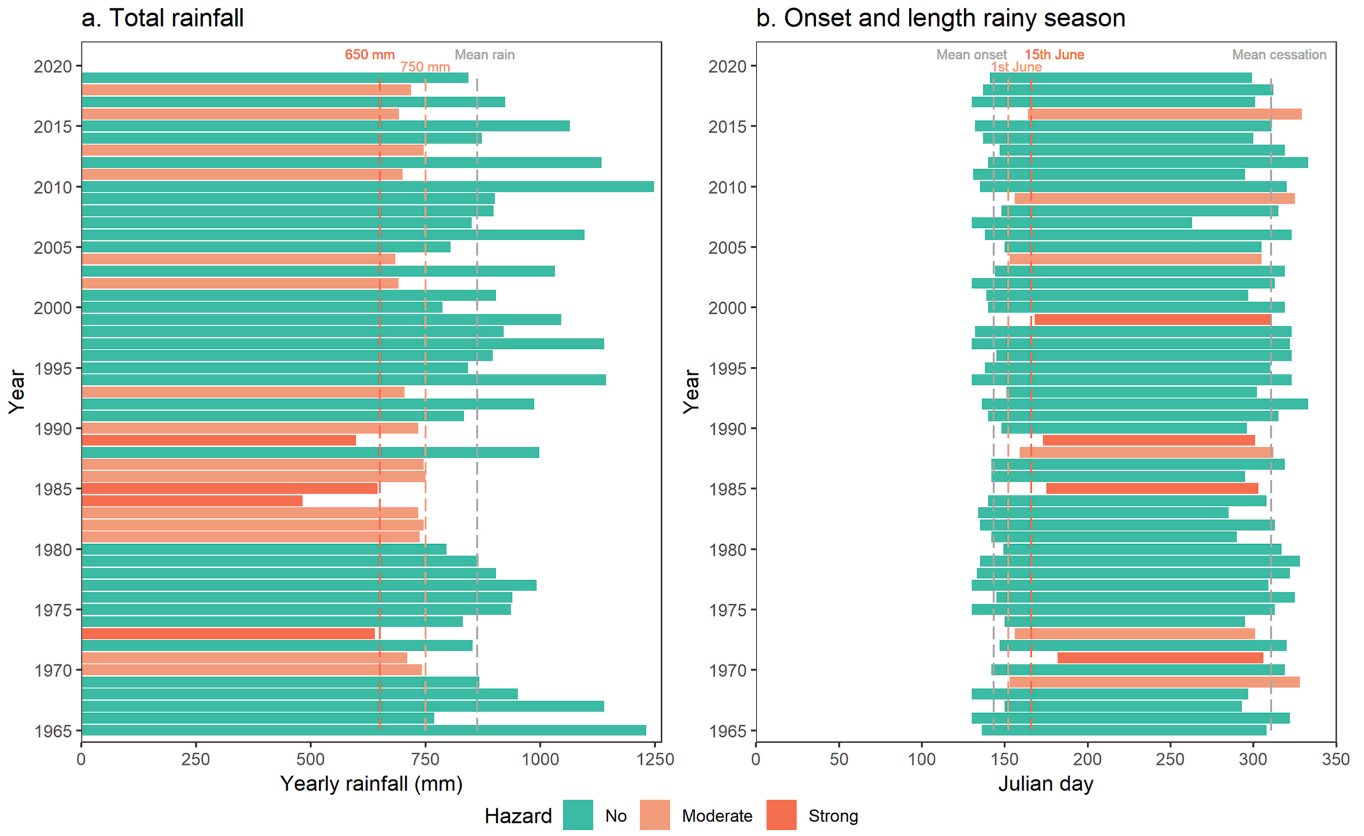

Fig. 1. Overview of years (1965–2019) from the N'Tarla weather data that carry a climatic hazard according to farmers' definitions. The grey dotted lines represent the average situation, the red dotted lines the hazard benchmark of total rain and day of onset. Years with hazards for total yearly rainfall (a) and onset of the rainy season (b) are coloured red for strong hazards and orange for moderate hazards.

crops to escape the early dry spells that are seen as most hazardous by farmers.

Of the non-weather hazards, a lack of good quality fertiliser influenced the mean yield negatively, especially for maize (Fig. 3d). Labour hazards, expressed by delayed sowing, also reduced cereal yields, although to a lesser extent (Fig. 3e).

3.3. *Cropping risk with farmers' practices*

The risk matrix combines the above findings on frequency and impact under baseline management (Fig. 4). Since the impact of dry spells (Fig. 3c) did not indicate a risk for cereal yields under baseline conditions, we excluded this hazard from further analysis on yield loss. The hazards that induced a larger yield loss occurred less often, suggesting that impact and frequency are inversely related. Sorghum responded differently than maize and millet to different types of hazards. For sorghum, yield losses were larger than for the two other cereals, except for the fertiliser hazard.

Under baseline conditions, the yield was largest and most stable for maize compared to the other two cereals (Table 3). The coefficient of variation was largest for sorghum (0.49) while it remained below 0.2 for millet and maize. Among the hazards, a low total rainfall occurred most often but had relatively little impact on maize and millet (8 % and 5 % yield loss respectively), but affected sorghum with 24 % yield loss. Also the impact of a late onset and the labour hazard was larger for sorghum (65 % and 32 % yield loss respectively), compared with maize (17 % and 5 %) and millet (12 % and 3 %). A late onset and labour hazard both happened around once every five years. Fertiliser hazards occurred rarely, once every ten years, but had a large effect on maize yields (54 % yield loss), followed by millet (19 %) and sorghum (9 %).

The risk of simultaneous hazards was not larger than that of the individual hazards, since the frequency decreased and the impact only increased to a limited extent (not more than 10 %) compared with the impact of the most influential hazard. However, for millet and sorghum, a labour hazard combined with a late onset or a low total rainfall increased the yield loss substantially (more than a 10 % point increase).

3.4. *Optimal management*

First, we defined the optimal level per factor with the other management factors held constant under baseline conditions. The optimal N rates were 66 kg N / ha, 27 kg N / ha, and 111 kg N / ha for maize, sorghum and millet respectively (Table 3b). The optimal sowing date was 22 days, 2 days, and 27 days after onset for maize, sorghum and millet, whereas the optimal variety was the short duration variety for maize and sorghum, and the long duration variety for millet.

Secondly, when allowing for interaction between management factors, the optimal levels shifted (Table 3b, NO*SO*VO). Generally, when sowing date or variety were optimised, the optimal N rates were larger. With optimal N rates and variety, the optimal sowing date for maize remained similar, while for sorghum and millet it was brought forward. The average optimal sowing date of sorghum (baseline variety) even appeared before the onset, suggesting that the drought tolerance at early vegetative stages of the sorghum baseline variety is strong enough to benefit from the minor rainfall events that lead up to the onset of rains. The optimal combined management included the baseline variety for sorghum, while for maize the short and for millet the long duration variety.

The optimised management was based on maximum yields, with for N application a limit when the profit from additional yield became equal to the cost of additional input. However, not only the absolute yield matters but also the stability of the yield over the years (Table 3).

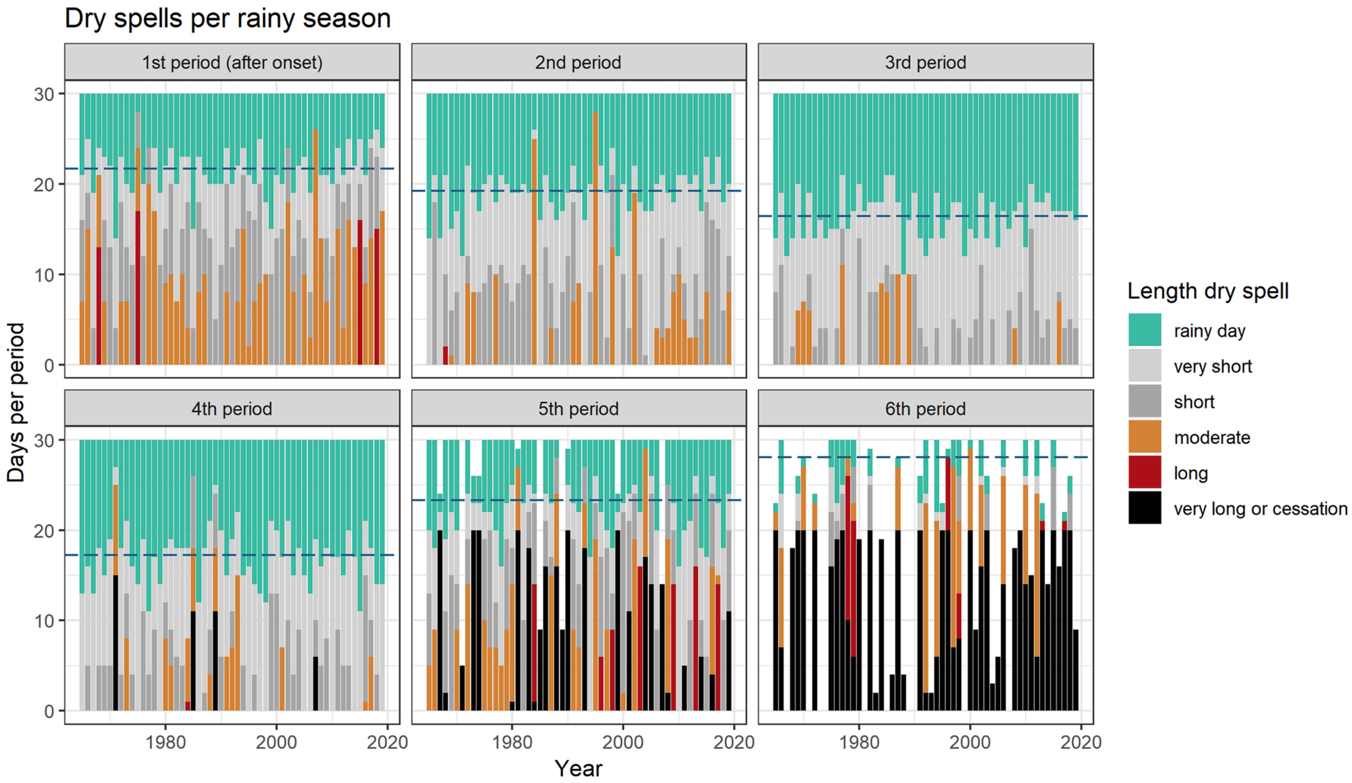

Fig. 2. Number of dry days within six subsequent 30-day periods counting from the onset (numbered in the facet label). The colours represent the length of the dry spell the day belongs to, being a very short dry spell (1–3 days), a short dry spell (4–6 days), a moderately long dry spell (7–13 days), or a long dry spell (14–20 days). The dotted blue lines represent the average number of dry days within that period. The black bars represent the dry days leading up to the cessation of the rainy season. A dry day is defined as receiving less than 1 mm of rainfall.

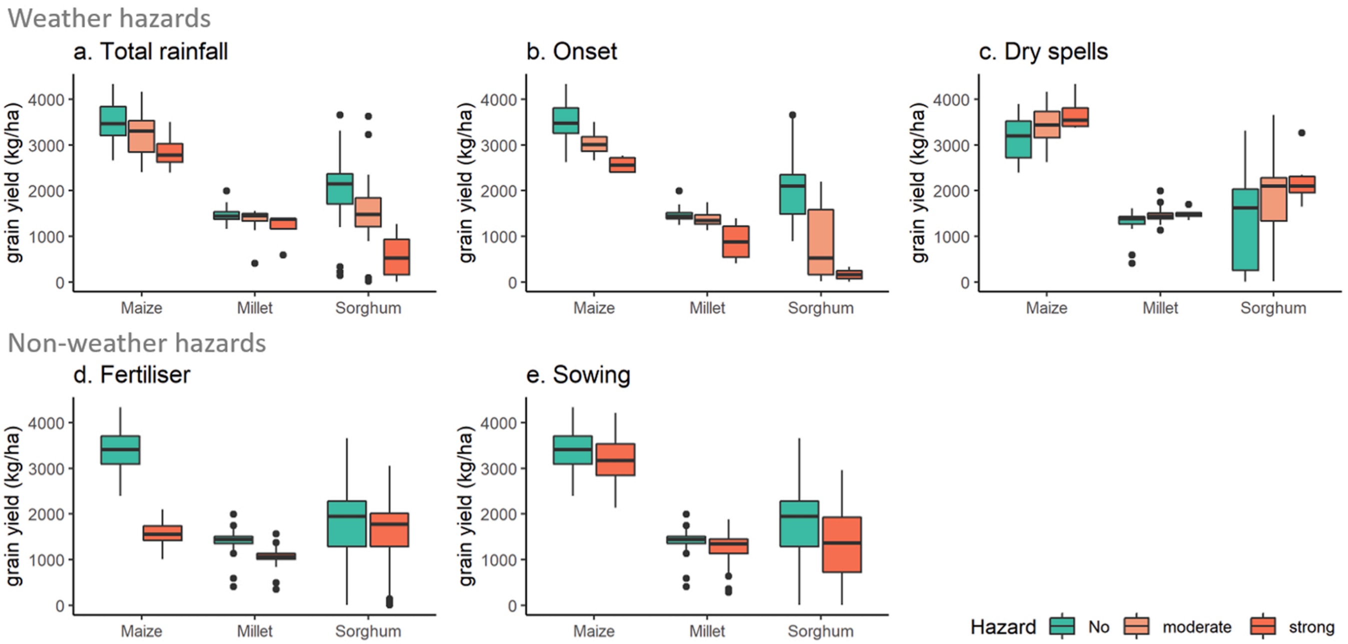

Fig. 3. Cereal yields under baseline crop management for years with and without weather hazards, and for management reflecting non-weather hazards. The definitions of the hazards are given in Table 2 and section 2.5.2. a) Years with a moderate hazard of low total rainfall (n = 15) and a strong hazard (n = 4) are compared with higher rainfall years (n = 36). b) Years with a moderate hazard of a late onset (n = 6) and with a strong hazard of a very late onset (n = 4) are compared with years with a normal onset (n = 45). c) Years with a moderate hazard (n = 35) and a strong hazard of dry spells (n = 6) are compared with years with shorter dry spells (n = 14). d) Baseline management is compared to management reflecting the fertiliser hazard (no N applied) for all 55 years. e) Baseline management is compared to management reflecting the labour hazard (sowing two weeks delayed) for all 55 years.

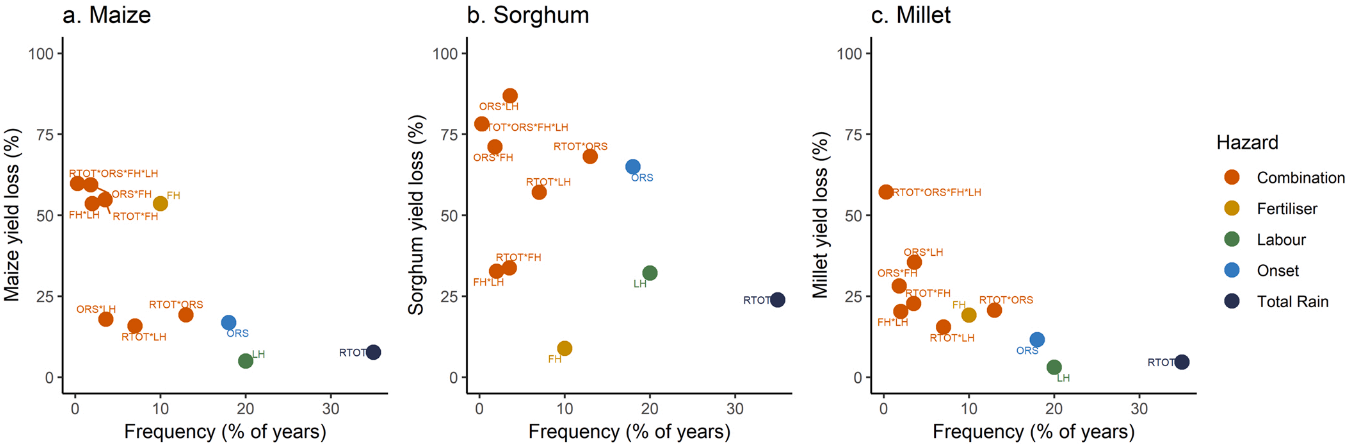

Fig. 4. Risk matrix with cereal yield loss plotted against frequency of hazards for a) maize, b) sorghum and c) millet, under baseline management for two weather hazards (late onset (ORS) and low total rain (RTOT)), two non-weather hazards (no fertiliser (FH) and labour (LH)) and their combinations.

Table 3
Factor combinations, of variety, N rate and sowing date (DOS), that represent the baseline, a certain hazard, recommended management, or the optimal treatment (average of treatments that maximised yield, with the standard deviation between brackets) for the three cereals on sandy soils. For each treatment the average yield (t / ha) and coefficient of variation is presented. Variety 1 represents the baseline, Variety 2 the short duration and Variety 3 the long duration variety.

Type of treatment	Code	Treatment description	Crop	Variety	N rate [kg N / ha] (sd)	DOS [days after onset] (sd)	DOS [date]	Yield [t / ha]	Coefficient of variation	Explanation
a) Baseline	BL	Baseline situation	Maize	Baseline	50	36	28th June	3.39	0.13	Farmers' practices
			Sorghum	Baseline	10	39	1st July	1.74	0.49	
			Millet	Baseline	15	23	15th June	1.33	0.17	
b) Optimal	NO	BL + optimal N	Maize	Baseline	66 (15)	36	28th June	3.60	0.18	Average N rate that gives the largest yield with an economic margin > 0
			Sorghum	Baseline	27 (23)	39	1st July	2.65	0.27	
			Millet	Baseline	111 (16)	23	15th June	2.93	0.12	
	SO	BL + optimal sowing date	Maize	Baseline	50	24 (26)	16th June	3.63	0.10	Average sowing date that gives the largest grain yield per year
			Sorghum	Baseline	10	2 (20)	25th May	2.67	0.16	
			Millet	Baseline	15	27 (22)	19th June	1.47	0.12	
	VO	BL + optimal variety	Maize	Short	50	36	28th June	4.62	0.16	Variety that most often gives the largest grain yield
			Sorghum	Short	10	39	1st July	2.27	0.14	
			Millet	Long	15	23	15th June	1.54	0.13	
	NO*SO*VO	BL + optimal N + sowing + optimal variety	Maize	Short	68 (10)	24 (27)	16th June	5.63	0.11	Average N rate, sowing date and variety that gives the largest yield (with economic margin >0)
			Sorghum	Baseline	85 (24)	-10 (13)	13th May	4.19	0.26	
			Millet	Long	160 (25)	4 (19)	27th May	4.04	0.12	

Optimising N management more than doubled yield for millet and lowered the coefficient of variation (CV). Sorghum yields increased by 50 %, while halving the CV. Optimising N resulted in a limited benefit for maize yield (less than 20 % increase) while it increased variability. The optimal N rates for millet were much higher than those for maize and sorghum, which is related to a different fertiliser response and a better price for millet grain. Although also beneficial for maize and millet, sowing earlier or cultivating a short duration variety, especially benefitted sorghum both in terms of absolute yields (50 % yield increase) and yield variability (CV dropping below 0.2). For sorghum the lag between optimal and farmers' sowing dates spanned more than five weeks, while for maize and millet this gap was less than two and one week respectively. Optimising the variety increased maize and sorghum yields with about a third, while it reduced the coefficient of variation of sorghum to below 0.2 and did not affect the CV of maize much. Benefits for millet were less striking.

Yield of all three cereals benefitted from optimising all management practices simultaneously compared with optimising one factor at a time. The gain was mainly in a raise in absolute yields, while for sorghum the CV was also reduced.

3.5. Cropping risk with optimal management

Adapting crop management alters the risks associated with various

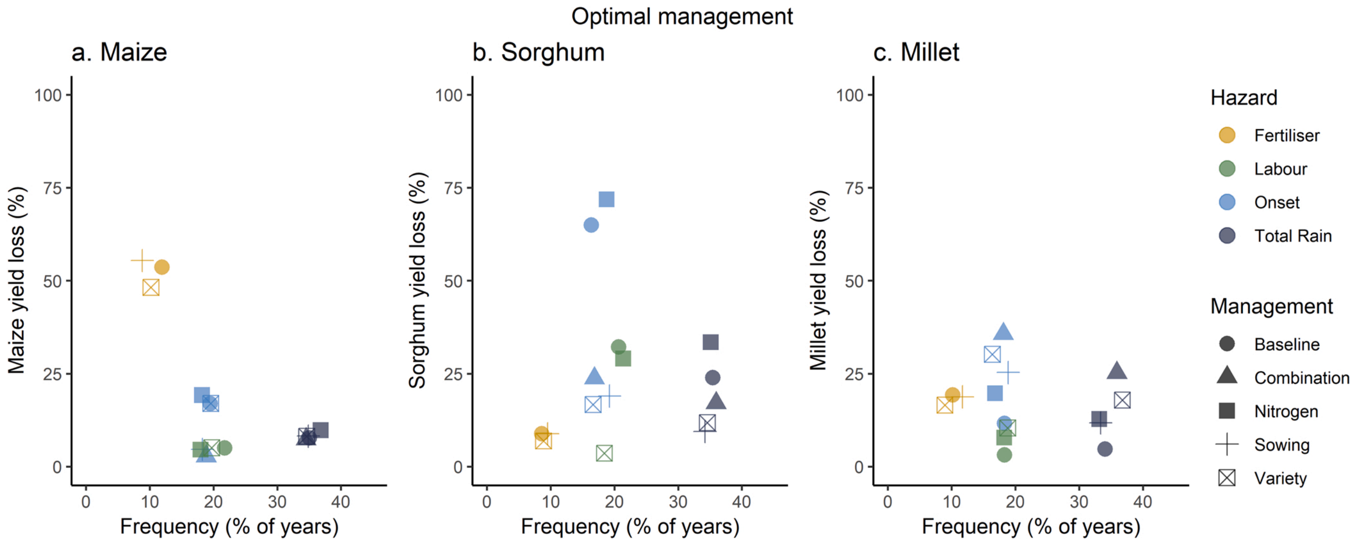

Fig. 5. Risk matrix with cereal yield loss plotted against frequency of hazards for a) maize, b) sorghum, and c) millet, under baseline and optimal management for two weather hazards (late onset and low total rain), two non-weather hazards (no fertiliser and labour). Optimal management reflected optimal N rates, sowing date and variety, or a combination of these three factors (Combination), as described in Table 4.

hazards (Fig. 5), and the changes in risk were more pronounced for sorghum and millet than for maize. The relative yield loss of maize under optimal management remained fairly similar (less than 10 % point difference in yield loss) compared with baseline management for all hazards. The late onset of the rainy season was the exception, where the yield loss reduced from 17 % to 3 % when optimising all management factors combined, and to 5 % when only optimising sowing dates. Thus overall, optimal management improved maize yields and did not increase the risk.

For sorghum, most optimal management options reduced, or did not influence, the relative yield loss (compared to yield loss under baseline management). This means that optimal management that increased absolute yields, did not increase risks in general. Sorghum yield losses were only slightly exacerbated when applying optimal N rates in the case of weather hazards, yet with less than 10 % point increase in yield loss. The other management practices decreased the yield loss in case of weather hazards. This was most pronounced for applying the optimal variety when rains started late (65–17 %) and for adapting sowing date when total rainfall was low (24–9 %). Cultivating the optimal short duration variety also induced a reduction in the yield loss for the labour hazard (32–4 %). The risk related to fertiliser hazards was less influenced by management.

Optimal management often increased relative millet yield losses under hazardous circumstances, contrary to what was the case for maize and sorghum. Nevertheless, the differences were negligible for the fertiliser and labour hazards. The yield loss was greatest when combining management (N rate, sowing date and variety) when a late onset (increasing from 12 % to 36 %) or low rainfall (5–25 %) occurred. While optimised N rates contributed most to the absolute yield increase for this combined management of both weather hazards, they contributed relatively little to worsening relative yield loss.

3.6. *Crop response to baseline and optimal management within a window of management options*

Baseline and optimal management are only a selection of management options farmers have. To better understand the crop response to adapted management, we examined in detail the yield response to the

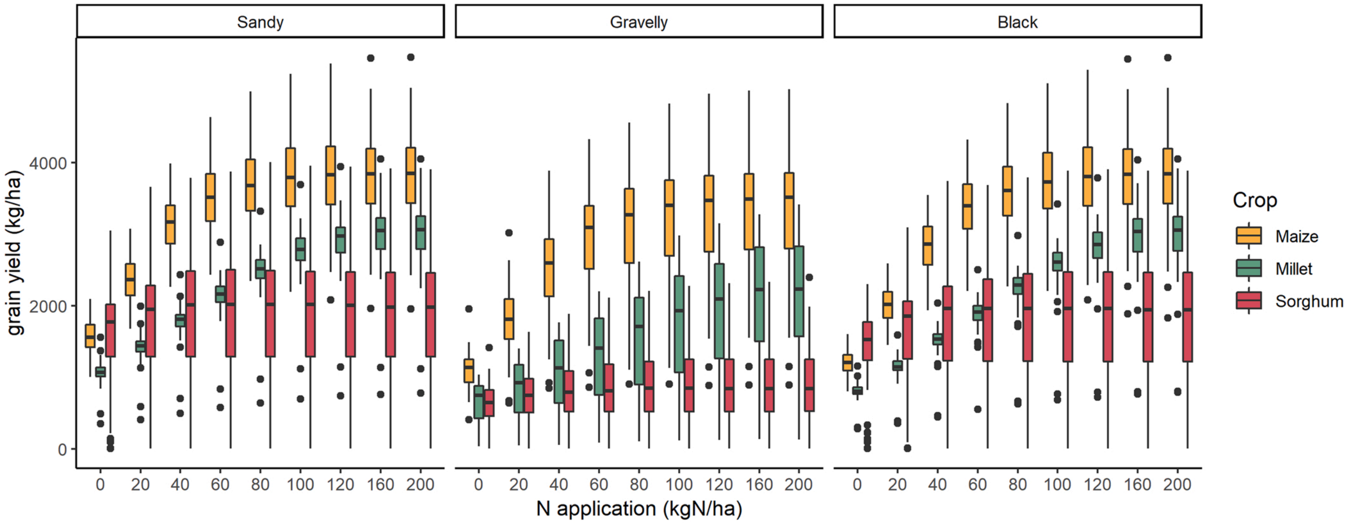

Fig. 6. Response curve of maize, sorghum and millet grain yield to different rates of N application on three soil types (sandy, gravelly and black soils) with baseline sowing date and variety.

interaction of a range of levels of management factors (soil, variety, N rates and sowing date) over the 55 years.

Firstly, we explored the interaction of N rates with soil types. The cereals yielded similarly on sandy (baseline) and black soils, but yields were less and more variable on the shallow gravelly soils (Fig. 6). With small N rates, sorghum outperformed maize and millet on sandy and black soils, but not on gravelly soils. Nevertheless, sorghum responded little to N addition, and millet and maize yields were better than sorghum yields at larger N application rates on all soil types. Although maize yielded best at almost all N application rates, millet yields showed less variability and plateaued at larger rates (around 140 kg N / ha). Maize yields plateaued at around 100 kg N / ha, and sorghum around 40 kg N / ha.

Secondly, we scrutinised the interaction between variety, sowing date and N rate. The yields and N response curves changed when adapting sowing dates. Focusing on sorghum, which benefited most from optimising the sowing date, we compared the average yields of optimal sowing dates with that of the least optimal sowing date for the three varieties (Fig. 7a). Without adding fertiliser, sorghum yields ranged from an average of 0–2 t / ha between least optimal and optimal sowing dates. The baseline sorghum variety yielded best (at optimal sowing date), except at small N rates when the short duration variety (CSM63E) yielded equally well, yet with a weaker N response. At larger N rates the longer duration and short duration varieties gave similar yields. In most years, it appeared optimal to sow the baseline and long duration variety early in the sowing window (Fig. 7b). For the short duration variety, it was often beneficial to wait until mid-June to sow; in about half of the years the optimal sowing date was after the 10th of June, regardless of the N rate. When small rates of N were applied, the optimal sowing dates were generally more spread out and later than with high N rates, for all varieties. Yield losses could reach 25 %, when sowing only five days earlier or later than the optimal sowing date, and crops could entirely fail when sowing was postponed by two months. With small N rates the relative yield loss was similar when sowing too early or too late, while with larger N rates the yield penalty was larger when sowing too late, explaining the optimal management combination of high N rates with early sowing.

Maize and millet had a similar, yet less pronounced, behaviour (Fig. S1 and S2). Yields also improved considerably when sowing dates were optimised to relatively early in the season (early to mid-June). When applying less N, it appeared beneficial to sow millet and maize later (Fig. S1). The long duration variety of millet yielded slightly better than the two other varieties, but when sowing late, the difference in yield between the varieties disappeared, which explains that the optimised management contains the interaction of the long duration variety at large N rates and early sowing. The difference in yield between optimal and least optimal sowing date was least pronounced for maize (Fig. S2). The short duration maize variety yielded best across all N rates. The baseline and long duration variety had similar yields, but the long duration variety benefitted more from large N rates.

4. Discussion

4.1. Frequency of production hazards

The prevalence of dry spells, insufficient total rainfall and late onset of the rains confirmed the hazardous nature of agriculture in southern Mali. In an earlier study in the same region, farmers perceived that these three weather hazards have become more frequent and severe over time, which they attributed partially to climate change (Traore et al., 2015). Nevertheless, no significant changes in rainfall variability (onset and total rain) were found over time (1965–2005), except for an increase in total number of dry days and an increase in minimum daily temperature (Traore et al., 2013). This is in line with the findings of the latest IPCC report on West Africa, that stated an increase in temperature accompanied by higher variability of precipitation (e.g. fewer but more intense rainfall events) (Trisos et al., 2022).

Dry spells were more complex to define and interpret than the two

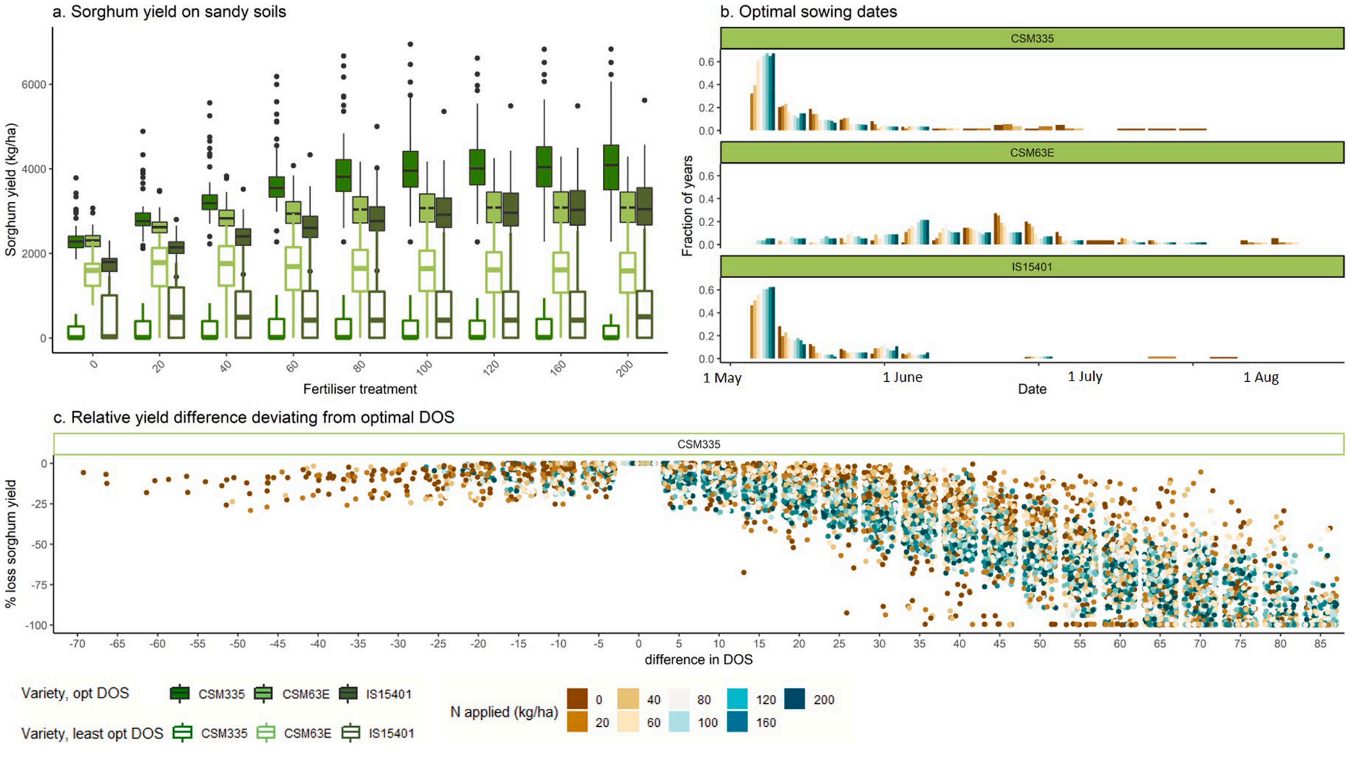

Fig. 7. a) Sorghum yield for different fertiliser rates and varieties on sandy soils, for the defined optimal sowing date (DOS) of each year (filled boxplots) and the least optimal DOS of each year (open boxplots). b) Histogram of the optimal sowing dates for the different years and c) Relative yield loss when deviating from the optimal sowing date for the baseline variety. Nine N rates (0 kg N / ha - 200 kg N / ha) and three varieties are represented.

other weather hazards. The severity does not only depend on the number, but also on the sequence and timing of dry days as farmers deemed the hazard stronger if more and longer dry spells occurred early after the onset of the growing season. Hence, the impact depends a lot on the sowing date, which was relatively late for sorghum, and only somewhat earlier for maize and millet, which explains why we did not discern yield losses related to this hazard under baseline conditions (Fig. 3). In Koutiala, farmers first sow the cotton fields, thus delaying sowing of the cereals (Soumaré, 2008). Another possible reason for not observing a negative impact on cereal yields could be that hazardous dry spells occurred more often in years with a relatively early onset of rains and high total rainfall, both positively related to yields.

By considering only the hazards that farmers perceived as most important, some weather characteristics were not taken into account. For example, rising temperatures (Traore et al., 2013) are known to result in shorter crop cycles, or induce grain sterility (Bassu et al., 2014). There is agreement that temperatures will further rise due to climate change, while for precipitation the climate models are more uncertain on the direction of change, although the frequency of more intense rainfall events is expected to increase (Roudier et al., 2011; Niang et al., 2014; Sultan et al., 2019; Trisos et al., 2022).

Our risk assessment comes with some uncertainty as the frequency of weather hazards depended on farmers' definition of the hazards, while the frequency of the non-weather hazards was entirely based on their perception. Farmers tend to have several biases that lead to either under-estimating or over-estimating the probability of a hazard, with the latter particularly common for hazards that have recently taken place (Hardaker et al., 2015). In our assessment, we reduced the amount of N application to zero in case of poor fertiliser quality. This is only valid in the most extreme case, but could also be a result of other circumstances (e.g. lack of access to fertiliser). The most important hazards for farmers were related to labour issues. As the start of the season is a critical period for farmers' decision making (Traore et al., 2014), we mimicked labour hazards by inducing late sowing in our analysis, while we did not take into account effects on weeding and harvest time. Although late sowing avoids water stress due to early season dry spells (Fig. 3), there are also negative effects of delayed farming practices (Wolf et al., 2015), for example from plants missing the possible benefit from the N flush with the first rains (Milgroom and Giller, 2013; Masvaya et al., 2018).

4.2. Management influences yields and impact of hazards

Under baseline conditions maize outperformed millet and sorghum in all studied circumstances, except in cases of fertiliser hazard when sorghum yielded more than maize (Fig. 2, Fig. 4). Farmers generally applied more N to maize than to sorghum and millet, which is justified since maize responded strongly to N application, and sorghum performed relatively well without N (Fig. 4, Fig. 3d). These crop characteristics drive farmers' choice to grow sorghum in semi-arid areas as well as maize in case fertiliser is available (Kante et al., 2019). Millet yielded less than sorghum and maize at low N rates, but surpassed yields of sorghum when more N is applied. The benefit of millet resided in its low yield variability (low CV in Table 3), and less sensitivity to the weather hazards (Fig. 3). Indeed, millet is often promoted as the more drought tolerant cereal (Ewansiha and Singh, 2006), and it increases in importance north of Koutiala where the climate becomes increasingly drier and hotter.

Adapting management aspects does not only influence average yields but the potential impact of different hazards as well. The hazards of late onset of the rainy season and the lack of labour are closely related. In Malian cropping systems, late sowing often results in yield losses in maize, sorghum and cotton (Traore et al., 2014) while a late starting date of the rainy season forces farmers to adapt their planning and affects the feasibility of crop varieties, with short duration varieties usually having smaller potential yields (Traore et al., 2017). Our analysis nuanced this commonly spread information: early sowing is a good strategy, but in some circumstances it could also be beneficial to wait, for example when applying low N rates (Fig. 7). Short duration varieties of maize and sorghum yielded most and reduced the yield losses when there was a late onset of the rainy season (Table 3 and Fig. 5). The use of photoperiodic sensitive varieties of millet and sorghum, which flower and mature at the same time of the year regardless of their sowing date, could allow for more flexibility in targeting the optimal sowing date (Traore et al., 2014; Faye et al., 2018b). Since labour is a bottleneck for farmers, with a lot of activities in the beginning of the season, and farmers' first focus is cotton, we hypothesise that farmers will be interested to sown cereals later when this can be done without much yield penalty. Also for the hazard of total rainfall, adapting the variety or sowing date reduced risk most while increasing yield, compared to adapting N rates. Increasing N rates even increased the risk of sorghum yield losses under weather hazards.

The optimised management treatments differed from what is currently advocated in the region. For example, CMDT (Compagnie Malienne pour le Développement du Textile) recommends maize fertiliser rates of 80 kg N / ha (Falconnier et al., 2016; Traore et al., 2017), whereas the recommended rates for both millet and sorghum in the Sudano-Sahelian region are around 40 kg N / ha (Kanté, 2001; Akponikpè et al., 2010; Traore et al., 2017; Amouzou et al., 2019). For maize (66 kg N / ha) and sorghum (27 kg N / ha) our simulation results indicated lower optimal N rates, while for millet the optimal rates were much higher (111 kg N / ha). Nevertheless, since the risk increased for several hazards by applying such high fertiliser rates for millet, lower N rates may be more appropriate for farmers (Akponikpè et al., 2010). Recommended management further included using a short duration variety (Niang et al., 2014) and the strategy of farmers to sow as early as possible (Huet et al., 2020). In our simulations for millet the long duration variety led to the highest yield, which is in line with other model findings for Niger and Mali (Singh et al., 2017).

4.3. Risk mitigation

Much literature stresses the importance of not only considering maximum average yields in volatile environments, but to include variability in the analysis (Urruty et al., 2016; Vanlauwe et al., 2016). Our analysis revealed differences in trade-offs between maximising yields and mitigating risk between the three cereals. Sorghum had the highest crop production risk of the three cereals, yet benefitted most from applying optimal management since it increased yields and simultaneously reduced yield losses under hazards. Millet had a comparable risk to maize, but for millet the risk often increased when adapting management to optimise yields. Applying optimal management for maize did not increase the risk. These different responses of cereals show the multiple options within the decision space of farmers when planning field and farm management.

Farmers prepare for, and deal with, several hazards by adapting field management practices related to, for example, fertiliser application, choice of varieties and sowing dates (Huet et al., 2020). Some hazards allow for a reactive flexible response, which means crop management can be adapted as the season progresses (Piha, 1993; Andrieu et al., 2015). For example, when the onset of the rainy season is late, farmers have time to adapt the sowing date, variety and allocation of fertilisers, without losing much investments. This could be especially useful for millet since the relative impact of the hazard increases under optimal management compared with baseline millet management, or in other words, investing in yield increasing management is less beneficial for millet in case of late onset the rainy season. Andrieu et al. (2015) described that farmers in Burkina Faso plan and implement operational flexibility options of adapting crop choice, land allocation, and input use, confirming that the options analysed in our study are within the decision portfolio of farmers. The potential of reactive flexibility was demonstrated since it limited farm gross margin variability (Andrieu et al., 2015). Piha (1993) suggested to split fertiliser applications so that the amount of N applied as top-dressing could be adjusted to the likely crop demand as the season develops. From our results, such an approach could be useful for millet and sorghum fields, where higher fertiliser use increased the risk when rainfall is limiting. Overall, maintaining a short-term operational flexibility requires an enabling environment that foresees access to inputs and labour throughout the growing season, as well as storage facilities. Currently, access to subsidised fertilisers on credit for cotton and maize production is readily available through the parastatal CMDT during the planning phase in August-September, more than half a year before the actual start of the rainy season. Apart from input supply through CMDT, access to mineral fertiliser through other sources or later in the year is difficult for farmers (Koné et al., 2020b). Additionally, access to improved cereal varieties is limited in the region (Koné et al., 2020a). Other hazards occurring at later stages or after crop growth, cannot readily be addressed by reactive flexible management. Longer term strategies like maintaining farm diversity of crops and management or keeping a strategic buffer of resources to maintain flexibility are more suitable for dealing with such hazards.

Diversifying to spread the risk by growing more crops, more varieties of crops and with differing management might be beneficial since crops responded differently to hazards and management (van Noordwijk et al., 1994). Farmers often cultivate several sorghum varieties on their farm (Siart et al., 2008), but not so much for maize and millet, although they intercrop many cereal fields with legumes as a within-field diversification of crops (Ganeme et al., 2021). Targeting or spreading sowing dates requires access to labour. Good access to animal and human health care may reduce the frequency of the labour hazard, while mechanisation tools potentially make field practices more efficient and reduce the delay of sowing in case there is a lack of manual or animal labour. Policies that support farmers to maintain these strategies of diversification and flexibility by for example enabling continuous access to inputs, storage facilities, weather forecasts or mechanisation, would contribute to increased resilience to risks.

4.4. Limitations of tools and further research

The DSSAT-CERES crop model is able to predict maize and sorghum crop yields in the Sudano-Sahelian region reasonably well (Adam et al., 2018; Worou et al., 2018; Falconnier et al., 2020). Nevertheless, the simulated yields in our study are higher than average observed yields under smallholder conditions (Traore et al., 2014; Falconnier et al., 2016), which could be due to hazards and management factors not taken into account, model characteristics, or parameter uncertainty. Firstly, yield reducing factors that are not taken into account in the model are for example the incidence of pests and diseases, bad weeding management, or lack of good quality inputs other than fertiliser, which are all potential stressors present in the area (Huet et al., 2020; Segnon et al., 2020). Secondly, DSSAT-CERES does not take into account soil nutrient dynamics other than N, and overall soil fertility was reflected through a single parameter (SLPF). In a comparative study, Falconnier et al. (2020) found that DSSAT-CERES was one of the more consistent crop models for maize yield simulation and that overall model uncertainty was relatively high for low-input systems where adequate calibration of soil processes is extremely important. Nevertheless, this comparative study did not find any increase in uncertainty of model response to rainfall with low N rates for the Mali case, which reflects our baseline situation. Lastly, parameter uncertainty may play a role, with cultivar settings for millet varieties particularly difficult to obtain. CIVT, which we used in the baseline, is a hybrid millet variety that has a higher yield potential than what is expected of the varieties used by farmers, which could partly explain the relatively good yields simulated by DSSAT (Faye et al., 2018a). Although all parameters were evaluated in literature, it is known that there is GxE interaction when cultivar parameters are calibrated (Fleisher et al., 2020), which could also have influenced our results when using these cultivars in slightly different circumstances. Nevertheless, in our study we focus on relative yield changes under changing circumstances rather than the absolute yields, keeping confidence in the model dynamics.

Farmers' criteria served as a starting point for our hazard selection and analysis, which makes the risk assessment relevant for stakeholders (Challinor et al., 2018). Nevertheless, the production hazards that farmers ranked highest among the perceived important hazards (Table 1) (Huet et al., 2020), were not necessarily the ones that bore the highest risk (frequency x impact) (Fig. 4). This discrepancy implied that farmers' risk perception sprouted from a farm perspective, also taking into account other crops and farm components. The analysis focused on cereal risks at field level, and gave insights in crop management that could increase production without increasing the variability and the risk. Other management practices that could be taken into account have a strong interaction with the livestock component of the farm, such as applying organic fertiliser or mulching (leaving the crop residues unavailable as animal feed). A next step to inform measures to build farmers' resilience would be to analyse how risk management and cereal production play out at farm level.

5. Conclusion

Our analysis revealed differences in trade-offs between maximising yields and mitigating risk between the three cereals. Sorghum had the highest crop production risk out of the three cereals, for all analysed hazards (late onset of the rainy season, low rainfall and sudden lack of labour) except for the fertiliser hazard. An additional hazard of labour shortage on top of weather hazards increased yield losses of millet and sorghum substantially. Nevertheless, sorghum benefitted most from applying optimal management since it increased yields and simultaneously reduced yield losses under hazards. Millet and maize had similar relative yield losses under hazards, but for millet the risk often increased when adapting management to optimise yields. Applying optimal management for maize did not increase the risk.

The management options we explored (adapting fertiliser rates, choice of varieties and sowing dates) are within the decision space of farmers and provided opportunity to increase yields. The analysed hazards all occurred more than once every ten years, making it relevant for farmers to take these hazards into account in their farm management decision making. Since the consequences on risks are different per crop, the interaction between management practices and hazards stress the importance to maintain farm diversity and operational flexibility. This requires an enabling environment that foresees storage capacities as well as year-round access to labour and inputs as fertiliser and varieties for farmers to build resilience.

CRediT authorship contribution statement

E.K. Huet: Conceptualization, Software, Methodology, Investigation, Visualisation, Writing – original draft**. M. Adam**: Conceptualization, Software, Writing – review & editing. **B**. **Traore**: Writing – review & editing. **K.E Giller** : Supervision, Writing – review & editing. **K. Descheemaeker** : Conceptualization, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126587.

References

Adam, M., Dzotsi, K.A., Hoogenboom, G., Traoré, P.C.S., Porter, C.H., Rattunde, H.F.W., Nebie, B., Leiser, W.L., Weltzien, E., Jones, J.W., 2018. Modelling varietal differences in response to phosphorus in West African sorghum. Eur. J. Agron. 100, 35–43. https://doi.org/10.1016/j.eja.2018.04.001.

Adam, M., MacCarthy, D.S., Traoré, P.C.S., Nenkam, A., Freduah, B.S., Ly, M., Adiku, S. G.K., 2020. Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: climate change or improved management practices. Agric. Syst. 185, 102920 https://doi.org/10.1016/j.agsy.2020.102920.

Akponikpè, P.B.I., Gérard, B., Michels, K., Bielders, C., 2010. Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. Eur. J. Agron. 32 (2), 144–154. https://doi.org/10.1016/j.eja.2009.09.005.

Akumaga, U., Tarhule, A., 2018. Projected changes in intra-season rainfall characteristics in the Niger River Basin, West Africa. Atmosphere 9 (12). https://doi.org/10.3390/atmos9120497.

Amouzou, K.A., Lamers, J.P.A., Naab, J.B., Borgemeister, C., Vlek, P.L.G., Becker, M., 2019. Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. Field Crops Res. 235, 104–117. https://doi.org/10.1016/j.fcr.2019.02.021.

Andrieu, N., Descheemaeker, K., Sanou, T., Chia, E., 2015. Effects of technical interventions on flexibility of farming systems in Burkina Faso: lessons for the design of innovations in West Africa. Agric. Syst. 136, 125–137. https://doi.org/10.1016/j.agsy.2015.02.010.

Aune, J.B., Bationo, A., 2008. Agricultural intensification in the Sahel – the ladder approach. Agric. Syst. 98 (2), 119–125. https://doi.org/10.1016/j.agsy.2008.05.002.

Bassu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., De Sanctis, G., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol. 20 (7), 2301–2320. https://doi.org/10.1111/gcb.12520.

Benjaminsen, T.A., Alinon, K., Buhaug, H., Buseth, J.T., 2012. Does climate change drive land-use conflicts in the Sahel. J. Peace Res. 49 (1), 97–111. https://doi.org/10.1177/0022343311427343.

Boansi, D., Tambo, J.A., Müller, M., 2019. Intra-seasonal risk of agriculturally-relevant weather extremes in West African Sudan Savanna. Theor. Appl. Climatol. 135 (1), 355–373. https://doi.org/10.1007/s00704-018-2384-x.

Bosma, R.H., Bos, M., Kanté, S., Kébé, D., Quak, W., 1999. The promising impact of ley introduction and herd expansion on soil organic matter content in southern Mali. Agric. Syst. 62, 1–15.

Brouwer, R., Akter, S., Brander, L., Haque, E., 2007. Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. Risk Anal. 27 (2), 313–326. https://doi.org/10.1111/j.1539-6924.2007.00884.x.

Bullock, J.M., Dhanjal-Adams, K.L., Milne, A., Oliver, T.H., Todman, L.C., Whitmore, A. P., Pywell, R.F., 2017. Resilience and food security: rethinking an ecological concept. J. Ecol. 105 (4), 880–884. https://doi.org/10.1111/1365-2745.12791.

Challinor, A.J., Muller, C., Asseng, S., Deva, C., Nicklin, K.J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J., Koehler, A.K., 2018. Improving the use of crop models for risk assessment and climate change adaptation. Agric. Syst. 159, 296–306. https://doi.org/10.1016/j.agsy.2017.07.010.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change. Agric., Ecosyst. Environ. 126 (1–2), 24–35. https://doi.org/10.1016/j.agee.2008.01.007.

Defrance, D., Sultan, B., Castets, M., Famien, A.M., Baron, C., 2020. Impact of climate change in West Africa on cereal production per capita in 2050. Sustainability 12 (18). https://doi.org/10.3390/su12187585.

Descheemaeker, K., Oosting, S.J., Homann-Kee Tui, S., Masikati, P., Falconnier, G.N., Giller, K.E., 2016. Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. Reg. Environ. Change 16 (8), 2331–2343. https://doi.org/10.1007/s10113-016-0957-8.

Dzotsi, K.A., Jones, J.W., Adiku, S.G.K., Naab, J.B., Singh, U., Porter, C.H., Gijsman, A.J., 2010. Modeling soil and plant phosphorus within DSSAT. Ecol. Model. 221 (23), 2839–2849. https://doi.org/10.1016/j.ecolmodel.2010.08.023.

Ewansiha, S.U., Singh, B.B., 2006. Relative drought tolerance of important herbaceous legumes and cereals in the moist and semi-arid regions of West Africa. J. Food, Agric. Environ. 4 (2), 188–190.

Ewert, F., Rötter, R.P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K.C., Olesen, J.E., van Ittersum, M.K., Janssen, S., Rivington, M., Semenov, M.A., Wallach, D., Porter, J. R., Stewart, D., Verhagen, J., Gaiser, T., Palosuo, T., Tao, F., Nendel, C., Roggero, P. P., Bartošová, L., Asseng, S., 2015. Crop modelling for integrated assessment of risk to food production from climate change. Environ. Model. Softw. 72, 287–303. https://doi.org/10.1016/j.envsoft.2014.12.003.

Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways: two decades of change in southern Mali. Agric. Syst. 139 (Supplement C), 210–222. https://doi.org/10.1016/j.agsy.2015.07.005.

Falconnier, G.N., Descheemaeker, K., Mourik, T.A.V., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. Field Crops Res. 187, 113–126. https://doi.org/10.1016/j.fcr.2015.12.015.

Falconnier, G.N., Corbeels, M., Boote, K.J., Affholder, F., Adam, M., MacCarthy, D.S., Ruane, A.C., Nendel, C., Whitbread, A.M., Justes, É., Ahuja, L.R., Akinseye, F.M., Alou, I.N., Amouzou, K.A., Anapalli, S.S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., Challinor, A.J., Chen, Y., Deryng, D., Elsayed, M.L., Faye, B., Gaiser, T., Galdos, M., Gayler, S., Gerardeaux, E., Giner, M., Grant, B., Hoogenboom, G., Ibrahim, E.S., Kamali, B., Kersebaum, K.C., Kim, S.H., van der Laan, M., Leroux, L., Lizaso, J.I., Maestrini, B., Meier, E.A., Mequanint, F., Ndoli, A., Porter, C.H., Priesack, E., Ripoche, D., Sida, T.S., Singh, U., Smith, W.N., Srivastava, A., Sinha, S., Tao, F., Thorburn, P.J., Timlin, D., Traore, B., Twine, T., Webber, H., 2020. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. Glob. Change Biol. 26 (10), 5942–5964. https://doi.org/10.1111/gcb.15261.

FAO. (2006). Guidelines for soil description (4th ed. ed.). Rome: Food and Agriculture Organization of the United Nations.

Faye, B., Webber, H., Naab, J.B., MacCarthy, D.S., Adam, M., Ewert, F., Lamers, J.P.A., Schleussner, C.-F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., Gaiser, T., 2018a. Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. Environ. Res. Lett. 13 (3), 034014 https://doi.org/10.1088/1748-9326/aaab40.

Faye, B., Webber, H., Naab, J.B., MacCarthy, D.S., Adam, M., Ewert, F., Lamers, J.P.A., Schleussner, C.F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., Gaiser, T., 2018b. Impacts of 1.5 versus 2.0 °c on cereal yields in the West African Sudan Savanna. Environ. Res. Lett. 13 (3) https://doi.org/10.1088/1748-9326/aaab40.

Fosu-Mensah, B.Y., Mensah, M., 2016. The effect of phosphorus and nitrogen fertilizers on grain yield, nutrient uptake and use efficiency of two maize (Zea mays L.) varieties under rain fed condition on Haplic Lixisol in the forest-savannah transition zone of Ghana. Environ. Syst. Res. 5 (1), 22. https://doi.org/10.1186/s40068-016-0073-2.

Fosu-Mensah, B.Y., MacCarthy, D.S., Vlek, P.L.G., Safo, E.Y., 2012. Simulating impact of seasonal climatic variation on the response of maize (Zea mays L.) to inorganic fertilizer in sub-humid Ghana. Nutr. Cycl. Agroecosyst. 94 (2–3), 255–271. https://doi.org/10.1007/s10705-012-9539-4.

Freduah, B.S., MacCarthy, D.S., Adam, M., Ly, M., Ruane, A.C., Timpong-Jones, E.C., Traore, P.S., Boote, K.J., Porter, C., Adiku, S.G.K., 2019. Sensitivity of maize yield in smallholder systems to climate scenarios in semi-arid regions of West Africa: Accounting for variability in farm management practices. Agronomy 9 (10). https://doi.org/10.3390/agronomy9100639.

Frison, E.A., Cherfas, J., Hodgkin, T., 2011. Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3 (1), 238–253. https://doi.org/10.3390/su3010238.

Fleisher, D.H., Haynes, K.G., Timlin, D.J., 2020. Cultivar coefficient stability and effects on yield projections in the SPUDSIM model. Agronomy Journal 112 (2), 828–843. https://doi.org/10.1002/agj2.20070.

Ganeme, A., Douzet, J.M., Traore, S., Dusserre, J., Kabore, R., Tirogo, H., Nabaloum, O., Ouedraogo, N.W.S., Adam, M., 2021. L'association sorgho/niébé au poquet, une pratique traditionelle en zone soudano-sahélienne à faible rendement: Etat des lieux et pistes d'amélioration. Int. J. Innov. Appl. Stud. 31 (4), 836–848.

Getnet, M.D. (2016). Crop intensification options and trade-offs with the water balance in the Central Rift Valley of Ethiopia. (PhD), Wageningen University, Wageningen. Retrieved from https://edepot.wur.nl/385687.

Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C., 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from CENTURY. Agron. J. 94 (3), 462–474. https://doi.org/10.2134/agronj2002.4620.

Gijsman, A.J., Thornton, P.K., Hoogenboom, G., 2007. Using the WISE database to parameterize soil inputs for crop simulation models. Comput. Electron. Agric. 56 (2), 85–100. https://doi.org/10.1016/j.compag.2007.01.001.

GYGA. (2020). Global Yield Gap and Water Productivity Atlas. Retrieved from www.yieldgap.org.

Hardaker, J.B., Lien, G., Anderson, J.R., Huirne, R.B.M., 2015. Coping with risk in agriculture: Applied decision analysis, Third ed.,. CABI, Oxfordshire, UK.

Hoogenboom, G., Porter, C.H., Shelia, V., Boote, K.J., Singh, U., White, J.W., Hunt, L.A., Ogoshi, R., Lizaso, J.I., Koo, J., Asseng, S., Singels, A., Moreno, L.P., Jones, J.W. (2019). Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7 (Version 4.7). Gainesville, Florida, USA: DSSAT Foundation. Retrieved from www.DSSAT.net.

Huet, E.K., Adam, M., Giller, K.E., Descheemaeker, K., 2020. Diversity in perception and management of farming risks in southern Mali. Agric. Syst. 184, 102905 https://doi.org/10.1016/j.agsy.2020.102905.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: a simulation model of maize growth and development. In: Texas, C.S. (Ed.), A&M Univ. Press.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3–4), 235–265. https://doi.org/10.1016/s1161-0301(02)00107-7.

Joseph, J.E., Akinrotimi, O.O., Rao, K.P.C., Ramaraj, A.P., Traore, P.S., Sujatha, P., & Whitbread, A.M. (2020). The usefulness of gridded climate data products in characterizing climate variability and assessing crop production. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) Working Paper. Wageningen, the Netherlands.

Kante, M., Rattunde, F., Nébié, B., Sissoko, I., Diallo, B., Diallo, A., Touré, A., Weltzien, E., Haussmann, B.I.G., Leiser, W.L., 2019. Sorghum hybrids for low-input farming systems in West Africa: Quantitative genetic parameters to guide hybrid breeding. Crop Sci. 59 (6), 2544–2561. https://doi.org/10.2135/cropsci2019.03.0172.

Kanté, S., 2001. Gestion de la fertilité des sols par classe d'exploitation au Mali-Sud. (PhD thesis). Wageningen University, Wageningen.

Khumairoh, U., Lantinga, E.A., Schulte, R.P.O., Suprayogo, D., Groot, J.C.J., 2018. Complex rice systems to improve rice yield and yield stability in the face of variable weather conditions. Sci. Rep. 8 (1) https://doi.org/10.1038/s41598-018-32915-z.

Kloos, J., Asare-Kyel, D., Pardoe, J., Renaud, F.G., 2015. Towards the development of an adapted multi-hazard risk assessment framework for the west Sudanian Savanna zone. UNU-EHS Working Paper 19.

Komarek, A.M., De Pinto, A., Smith, V.H., 2020. A review of types of risks in agriculture: what we know and what we need to know. Agric. Syst. 178. https://doi.org/10.1016/j.agsy.2019.102738.

Koné, Y., Smale, M., Thériault, V., Sissoko, M., Assima, A., Keita, N. (2020b). Malian Farmers' Access to Fertilizer Is Challenged by COVID-19 [Press release]. Retrieved from https://www.canr.msu.edu/news/how-is-covid-19-worsening-food-insecurity-in-mali-1.

Koné, Y., Smale, M., Bokary, T. (2020a). Politique et reglementation semencière au Mali; Reflection sur les indicateurs d'acces de petits producteurs aux semences de qualité. Retrieved from https://ageconsearch.umn.edu/record/303625.

Losch, B., Fréguin-Gresh, S., White, E.T., 2012. Structural transformation and rural change revisited: challenges for late developing countries in a globalizing world. African Development Forum Series. World Bank, Washington DC.

Mach, K.J., Kraan, C.M., Adger, W.N., Buhaug, H., Burke, M., Fearon, J.D., Field, C.B., Hendrix, C.S., Maystadt, J.F., O'Loughlin, J., Roessler, P., Scheffran, J., Schultz, K.A., von Uexkull, N., 2019. Climate as a risk factor for armed conflict. Nature 571 (7764), 193–197. https://doi.org/10.1038/s41586-019-1300-6.

Masvaya, E.N., Nyamangara, J., Giller, K.E., Descheemaeker, K., 2018. Risk management options in maize cropping systems in semi-arid areas of Southern Africa. Field Crops Res. 228, 110–121. https://doi.org/10.1016/j.fcr.2018.09.002.

Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., de Mey, Y., Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, P.M., Candel, J. J.L., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.-J., Peneva, M., Gavrilescu, C., Reidsma, P., 2019. A framework to assess the resilience of farming systems. Agric. Syst. 176, 102656 https://doi.org/10.1016/j.agsy.2019.102656.

Milgroom, J., Giller, K.E., 2013. Courting the rain: Rethinking seasonality and adaptation to recurrent drought in semi-arid southern Africa. Agric. Syst. 118, 91–104. https://doi.org/10.1016/j.agsy.2013.03.002.

Mubaya, C.P., Mafongoya, P., 2016. Local-level climate change adaptation decision-making and livelihoods in semi-arid areas in Zimbabwe. Environ., Dev. Sustain. 19 (6), 2377–2403. https://doi.org/10.1007/s10668-016-9861-0.

Niang, I., Ruppel, O.C., Abrado, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P.. (2014). Africa. In V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, E. K.L., Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1199–1265). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Nissan, H., Goddard, L., de Perez, E.C., Furlow, J., Baethgen, W., Thomson, M.C., Mason, S.J., 2019. On the use and misuse of climate change projections in international development. Wiley Interdiscip. Rev.: Clim. Change 10 (3). https://doi.org/10.1002/wcc.579.

OMA. (2016). Retrieved from: http://www.oma.gov.ml/.

Piha, M.I., 1993. Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp. Agric. 29 (4), 405–415. https://doi.org/10.1017/S0014479700021128.

Ritchie, J.T., Singh, A., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G., Hoogenboom, G., Thornton, P. (Eds.), Understanding Options for Agricultural Production, Vol. 7. Springer, Netherlands, pp. 79–98.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: what does the recent literature say. Glob. Environ. Change 21 (3), 1073–1083. https://doi.org/10.1016/j.gloenvcha.2011.04.007.

Salack, S., Muller, B., Gaye, A.T., 2011. Rain-based factors of high agricultural impacts over Senegal. Part I: integration of local to sub-regional trends and variability. Theor. Appl. Climatol. 106 (1–2), 1–22. https://doi.org/10.1007/s00704-011-0414-z.

Schmitt Olabisi, L., Liverpool-Tasie, S., Rivers, L., Ligmann-Zielinska, A., Du, J., Denny, R., Marquart-Pyatt, S., Sidibé, A., 2017. Using participatory modeling processes to identify sources of climate risk in West Africa. Environ. Syst. Decis. 38 (1), 23–32. https://doi.org/10.1007/s10669-017-9653-6.

Schlecht, E., Buerkert, A., Tielkes, E., Bationo, A., 2006. A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. Nutrient Cycling in Agroecosystems 76, 109–136.

Segnon, A.C., Totin, E., Zougmore, R.B., Lokossou, J.C., Thompson-Hall, M., Ofori, B.O., Achigan-Dako, E.G., Gordon, C., 2020. Differential household vulnerability to climatic and non-climatic stressors in semi-arid areas of Mali, West Africa. Clim. Dev. https://doi.org/10.1080/17565529.2020.1855097.

Siart, S., Weltzien, E., Kanouté, M., Hoffmann, V., 2008. Farmers' sorghum seed sources after a drought year in southern Mali. Cah. Agric. 17 (2), 195–198. https://doi.org/10.1684/agr.2008.0181.

Singh, P., Nedumaran, S., Traore, P.C.S., Boote, K.J., Rattunde, H.F.W., Prasad, P.V.V., Singh, N.P., Srinivas, K., Bantilan, M.C.S., 2014. Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change. Agric. For. Meteorol. 185, 37–48. https://doi.org/10.1016/j.agrformet.2013.10.012.

Singh, P., Boote, K.J., Kadiyala, M.D.M., Nedumaran, S., Gupta, S.K., Srinivas, K., Bantilan, M.C.S., 2017. An assessment of yield gains under climate change due to genetic modification of pearl millet. Sci. Total Environ. 601–602, 1226–1237. https://doi.org/10.1016/j.scitotenv.2017.06.002.

Sivakumar, M., 1992. Empirical analysis of dry spells for agricultural applications in West Africa. J. Clim. 5 (5), 532–539. https://doi.org/10.1175/1520-0442(1992)005<0532:EAODSF>2.0.CO;2.

Soumaré, M. (2008). Dynamique et durabilité des systemes agraires a base de coton au Mali. (PhD), Université de Paris X Nanterre, Paris, France.

Sultan, B., Defrance, D., Iizumi, T., 2019. Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci. Rep. 9 (1), 12834. https://doi.org/10.1038/s41598-019-49167-0.

ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., de Groot, H.L.E., van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. Glob. Food Secur. 23, 9–21. https://doi.org/10.1016/j.gfs.2019.02.001.

Traore, B., Corbeels, M., van Wijk, M.T., Rufino, M.C., Giller, K.E., 2013. Effects of climate variability and climate change on crop production in southern Mali. Eur. J. Agron. 49, 115–125. https://doi.org/10.1016/j.eja.2013.04.004.

Traore, B., van Wijk, M.T., Descheemaeker, K., Corbeels, M., Rufino, M.C., Giller, K.E., 2014. Evaluation of climate adaptation options for Sudano-Sahelian cropping systems. Field Crops Res. 156, 63–75.

Traore, B., Van Wijk, M.T., Descheemaeker, K., Corbeels, M., Rufino, M.C., Giller, K.E., 2015. Climate variability and change in southern Mali: learning form farmer perceptions and on-farm trials. Exp. Agric. 51, 615–634.

Traore, B., Descheemaeker, K., van Wijk, M.T., Corbeels, M., Supit, I., Giller, K.E., 2017. Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. Field Crops Res. 201, 133–145. https://doi.org/10.1016/j.fcr.2016.11.002.

Trisos, C.H., Adelakan, E., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N.P., Zakieldeen, S., 2022. In Press). Africa. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerability. Cambridge University Press.

Urruty, N., Tailliez-Lefebvre, D., Huyghe, C., 2016. Stability, robustness, vulnerability and resilience of agricultural systems. A review. Agron. Sustain. Dev. 36 (1), 15. https://doi.org/10.1007/s13593-015-0347-5.

Van Dijk, H., De Bruijn, M., & Van Beek, W. (2004). Pathways to mitigate climate variability and climate change in Mali: the districts of Douentza and Koutiala compared. In A. J. Dietz, R. Ruben, & A. Verhagen (Eds.), The impact of climate change on drylands, with a focus on West Africa (pp. 173–206). Dordrecht: Kluwer Academic Publishers.

van Noordwijk, M., Dijksterhuis, G.H., Van Keulen, H., 1994. Risk management in crop production and fertilizer use with uncertain rainfall; how many eggs in which baskets. NJAS - Wagening. J. Life Sci. 42 (4), 249–269. https://doi.org/10.18174/njas.v42i4.588.

Van Wart, J., Grassini, P., Yang, H., Claessens, L., Jarvis, A., Cassman, K.G., 2015. Creating long-term weather data from thin air for crop simulation modeling. Agric. For. Meteorol. 209–210, 49–58. https://doi.org/10.1016/j.agrformet.2015.02.020.

Vanlauwe, B., Coe, R.I.C., Giller, K.E., 2016. Beyond averages: new approaches to understand heterogeneity and risk of technology success or failure in smallholder farming. Exp. Agric. 1–23 doi:Doi: 10.1017/s0014479716000193.

Wolf, J., Ouattara, K., Supit, I., 2015. Sowing rules for estimating rainfed yield potential of sorghum and maize in Burkina Faso. Agric. For. Meteorol. 214–215, 208–218. https://doi.org/10.1016/j.agrformet.2015.08.262.

World Bank, 2016. Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners. Agriculture Global Practice Discussion Paper Series 10.

World Bank. (2020). PPP conversion factor. Retrieved from https://data.worldbank.org/indicator/PA.NUS.PPP?end=2020&locations=ml&start=1990.

Worou, O.N., Tondoh, J.E., Sanou, J., Gaiser, T., Nikiema, P.M., Bayala, J., Bazié, P., Ky-Dembele, C., Kalinganiré, A. (2018). Intensifying Maize Production Under Climate Change Scenarios in Central West Burkina Faso. In Handbook of Climate Change Resilience (pp. 1–23).