REPUBLIQUE DU MALI

****

MINISTERE DE L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE SCIENTIFIQUE

****

UNIVERSITE DES SCIENCES, DES TECHNIQUES ET DES TECHNOLOGIES DE BAMAKO (USTTB)

****

ECOLE DOCTORALE DES SCIENCES ET TECHNOLOGIES DU MALI (EDSTM)

****

DOCTORATE THESIS

THEME:

ASSESSING DEFICIT IRRIGATION AND SUPPLEMENTAL IRRIGATION AS WATER MANAGEMENT STRATEGIES FOR IMPROVING MAIZE PRODUCTION IN BENIN

A THESIS

IN THE RURAL POLYTECHNIC INSTITUTE OF TRAINING AND APPLIED RESEARCH IN PARTNERSHIP WITH THE WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL), SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN CLIMATE CHANGE AND AGRICULTURE OF THE UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

Presented and supported on: 01/02/2020

By : Marsanne Gloriose Bignon ALLAKONON

JURY MEMBERS

President **:** Dr. Yacouba Diallo, Maitre de Conférences IPR-IFRA, Mali

Members :

Examiner **:** Dr. Amadou Apho BAH, Maitre de Conférences, IPR-IFRA, Mali

Reporter **:** Dr. Niaba TEME, Maître de Recherche, IER, Mali

Reporter **:** Dr. Chiaka Diallo, Maître Assistant, IPR-IFRA, Mali

Director **:** Dr. Ir. P. B. Irénikatché AKPONIKPE, Maître de Conférences, CAMES, Université de Parakou, Bénin

Co-director : Prof. Bernhard Tischbein, Center for Development Research, Bonn, Germany.

CONTENT

Dedication

To my late mother ODJO Bernadine,

Acknowledgements

I am so grateful to the WASCAL research Programme, funded by the German Ministry of Education. This programme offered opportunities to my colleagues including myself to conduct researches to benefit our home countries and contribute to solve relevant challenges. I am thankful to the former programme Director in Mali, Pr. Amoro Coulibaly, and to the new Director in office, Dr Diallo Yacoubou, as well as the coordination staffs of the Coordination.

I’m indebted to my main promotor, Dr. Ir P. B. Irènikatché Akponikpe for improving every steps of my scientific journey through his advices, although disguised, as well as his close follow up of every activity during the course of the thesis. My words cannot express my full gratitude, until I put the knowledge acquired in his laboratory into practice for the upcoming scientific journey. I’m grategul to my co-promotor Prof Tischbein Bernhard for his distant assistance, despite all his duties. I am also grateful to each member of the Complexe de l’Innovation, from the Students to the Professors and Doctors in different fields for their contribution to this work and to my general wellbeing. My special thanks goes to Dr Pierre Tovihoundji and Dr Zakari SISSOU for their technical assistance throughout this study. May God bless you abundantly more.

During my scientific stay in the HydroModE_Lab of my main promotor, I shared valuable memories with other students who contributed in various ways to the progress of this work, Kpadonou Esaie, Lipkete Didier, Adjogboto Andre, and Diallo Mariama. Thank you all for your help anytime I needed you around. I will not forget other collegues from other laboratory, Souley Adechian, Fructueuse Ouidoh, and Philippe Tchegnon for their different advices and care.

It would be merely impossible to achieve this work without a loving and caring family, and without a friend. To my father and my sisters, receive here my heartfelt gratitude for your care and your unceasing concern throughout my study. Thanks for enduring my absence away from home, to help me prepare a better future. Thanks to my friend Anselm Ndiukwu for his presence in my life.

The list is not surely exhaustive and I would extend my gratitude to all those whose names were not mentioned here. My words cannot express to deepness of my gratitude towards you all.

List of Acronyms and ABBREVIATIONS

DAS: Day after sowing

DI: Deficit irrigation

ET_0: Reference Evapotranspiration

ETc: Crop Evapotranspiration

ETr: Reel Evapotranspiration

FAO: Food and Agriculture Organization

GDP: Global Domestic Product

GYP: Grain Yield Percentage

IWUE: Irrigation Water Use Efficiency

Kg ha^{-1}: Kilograms per hectare

LAI: Leaf Area Index

Mm: Millimeters

OI: Optimal irrigation

ONASA : Officie National d'Appui à la sécurité Alimentaire

ONASA: Office National d’Appui à la sécurité alimentaire

PRESAO: Programme de Renforcement et de Recherche sur la Sécurité Alimentaire en Afrique de l’Ouest

RDI: Regulated Deficit irrigation

RS : Reproductive stage

SI: Supplemental Irrigation

SSA: Sub-Sahara Africa

UNEP: United Nations Environment Programme

VRS: Vegetative and reproductive stage

VS: Vegetative stage

WA: West Africa

WD: Water Deficit

WUE: Water Use Efficiency

List of Figures

List of Tables

List of Appendices

RESUME

L'objectif de cette étude était: (i) d'identifier les facteurs expliquant la réponse du maïs au stress hydrique (DI) de l'irrigation; (ii) évaluer le potentiel de l'irrigation par déficit en production de maïs; et (iii) évaluer le potentiel d'irrigation l'irrigation supplémentaire pour améliorer la production du maïs, au Bénin. Pour atteindre ces objectifs, une revue de littérature quantitative a été menée et des expérimentations ont été conduites. Trois expériences sur le terrain ont été menées à Parakou ; sous régime pluvial en 2018; sous régime pluvial plus irrigation supplémentaire en 2019; et sous quatre (04) niveaux de DI (0, 25, 50 et 75% ETc) pendant la saison sèche de 2019. Pour toutes les expérimentations, un bloc aléatoire avec 3 répétitions a été utilisé. La revue quantitative a montré que la perte de rendement augmente avec l'augmentation des niveaux de DI à tous les stades de croissance. Mais cette perte est minimale au stade végétatif. En outre, la réponse du maïs au stress hydrique dépend de nombreux facteurs tels que la zone climatique, les densités de culture, le cycle de la variété et les pratiques de gestion de la fertilité. Les résultats expérimentaux ont indiqué que l'indice de surface foliaire (LAI) et la hauteur des plantes diminuaient dans les traitements sous stress pendant la période d'application du stress. Le rendement en grains diminue à mesure que le stress hydrique augmente de 25%, 47% et 82% respectivement dans les traitements D25, D50 et D75. Il n'y avait pas de différence significative de la biomasse aérienne entre D0 et D25 d'un côté et entre D50 et D75 de l'autre côté. L'efficience d'utilisation de l'eau (WUE) et l'efficience d'utilisation de l'eau d'irrigation (IWUE) ont diminué à mesure que l'ID augmente, respectivement de 19% et 0,26% dans les traitements D25. Ces résultats impliquent qu'il existe un niveau d'irrigation déficitaire optimal pour lequel la perte de rendement serait réduite. Des perspectives de recherche ont été relevées dont la détermination de l'acceptabilité et de la viabilité économique de ces stratégies de recherche pour les producteurs.

ABSTRACT

Deficit Irrigation (DI) consists to provide the crop with water below its daily need (ETc) according to the sensitivity of its growth stages. The objective of this study was : (i) to assess the factors explaining maize response to irrigation water stress; (ii) assess the potential of supplemental irrigation and deficit irrigation for improving rainfed maize production; and (iii) to evaluate crop water productivity under irrigation water deficit in sub-humid climate of Benin. To achieve its objectives, the present study first reviewed through quantitative meta-analysis the overall response of maize to DI to identify the growth stage that will allow limited yield loss, and to understand the factors that explain maize response to water stress. Two field experiments were conducted under supplemental irrigation in 2018 and 2019 using four rates of fertilizers; and one experiment under deficit irrigation in 2019 using four (04) levels of DI (0, 25, 50, and 75% ETc). Irrigation water stress were applied based on daily crop evaporation determined from CropWat FAO database. For all experiments, a Randomized Bloc Design with 3 replications was used. The review showed that yield loss increases with increasing levels of DI at all growth stages, but yield loss was minimized in vegetative stage. In addition, the results from the review suggest that maize response to water stress is dependent on many factors such as climatic zone, cropping densities, and fertility management practices. The experimental results indicated that leaf area index (LAI) and plant height decreases in stressed treatments during the period of stress application, but the decrease was observed on different periods, suggesting a given sequence, or a process through which DI affect crop production. Grain yield decreases as water stress increases by 25%, 47%, and 82% respectively in D25, D50, and D75 treatments. There was no significant difference of stover yield between D0 and D25 in one side, and between D50 and D75 on the other side. Water Use Efficiency (WUE) and Irrigation Water Use Efficiency (IWUE) decreased as DI increases, respectively by 19% and 0.26% in D25 treatments, implying there’s an optimum deficit irrigation level for which yield loss would be reduced. Since farmers in West Africa context are more concerned about a sustained yield over a long period of time, that optimum deficit level should be determined, for instance through simulation on the long term base on scenario analysis, to make appropriate recommendations.

1.1. Context and rationale

1.1.1. Economic importance of Agriculture in West Africa

Agriculture is an important economic driver of growth in the world. In West Africa (WA), the share of agriculture in Global Domestic Product (GDP) has increased in most countries over the past two decades. In Benin for instance, agriculture sector accounts for about 40% of the GDP, and occupies about 70% of the active population who rely on it for their livelihoods. It is estimated that 208 millions of people in Sub-Sahara Africa depend on maize as the source of food security and of income. Despite its economic importance, agriculture is marked by low productivity with little application of science and technology, and unfavorable policies priorities (Chauvin et al, 2012). In Benin, the dependence of agriculture in general and more specifically cereal production systems (Cairns et al, 2013) limits not only the production of maize, but also the economic benefits its provide smallholder farmers.

1.1.2. Constraints for sustainable agriculture water management

The world is facing a general water crisis affecting every sector and above all, food security (Food and Agriculture Organization, 2016; Hanjra and Qureshi, 2010). Out of the 3% fresh water available on earth, 69% is extracted worldwide for agricultural purpose, mainly in the form of irrigation (Cassardo and Jones, 2011; Rosegrant et al., 2009). Fifteen to thirty five (15-35%) of the water withdrawn for irrigation in low and middle-income countries is used in an inefficient and unsustainable manner (Plessis, 2017). Through this process, much water is lost through excessive water use for crop, soil erosion, high evaporative demand, and runoff. For example, the Lake Tchad, which was once the largest freshwater lake in Africa, has shrunk by 90% in 40 years, due to irrigation and to some extent, desertification (Amali et al., 2016; Magrin, 2016). In addition, recurrent disturbances such as pollution of water bodies are afflicted to the hydrologic cycle. In the context of climate variability and climate change, reduction in precipitation, coupled with increased CO2 emission, is predicted to affect water quantity and quality available in many areas (Pulido-Velazquez et al., 2015; Stagl et al., 2014). In contrast, food demand is projected to increase by 70% by 2050 (Plessis, 2017). These considerations have left the agricultural sector with the double challenge of making 70% more food available to the world's growing population with less or decreasing fresh water resources (Ray et al., 2013). One way to overcome this challenge is to use irrigation methods and technologies that improve water use efficiency (WUE) (Evans and Sadler, 2008; Fereres and Soriano, 2006).

1.1.3. Problem Statement and analysis

1.1.3.1. Challenges for sustainable maize production

Maize is the most important staple food crop with 35% of total cereal area and 43% of total cereal production in Sub-Sahara Africa (SSA) (FAOSTAT, 2017). It covers 19% of the total area cultivated for cereals and accounts for one-fifth ($1/5^{th}$) of the calories and protein consumed by humans in West Africa (Smale, 2011). Through this way, it contributes largely to food security (Shiferaw et al., 2011).

In Benin, potential maize grain yield is generally less than 1.5 t ha^{-1}, compared to 5 to 6 t ha^{-1} in the top five maize producing countries in the world (PRESAO, 2011). In northern regions of Benin where the rainfall is unimodal (Djossou et al., 2017), this yield of 1.5 t ha^{-1} can be considered as the annual production that southern regions rely on in times of lack (ONASA, 2016). Many factors contribute to such low productivity. Among these factors, accessibility to and mobilization of water in and out of season for cereal production is a major concern that triggers smallholder farmers. The challenge of accessibility to and mobilization of water is common to farmers in all West Africa countries. To overcome that challenge which is more observed in dry seasons, some farmers adopt the production of cereals along the bank of rivers or streams to benefit from the wet conditions of the soils, and to double their annual income from crop production. In Togo for instance, Diwediga et al., (2012) reported that 80% of the off-season production of cereals is devoted to marketing to strengthen sources of income and compensate for the lack of food products in sub-humid regions such as Oti. But in Benin, very few farmers adopt this practice and rare studies have been interested in its feasibility, and the challenges that arise from it.

Until recently in 2017, annual maize production in Benin suffers from shortage and hardly meets the national demand. An evaluation of food production revealed a non-satisfaction of the high consumption demand in some southern regions of the country including Mono (87 tons of shortage), Ouémé (120.74 tons of shortage), Atlantique (154.95 tons of shortage), and Littoral (64.15 tons of shortage) (ONASA, 2016). Shortage of maize production in the southern part of the country is exarcerbated by bimodal rainfall pattern, yet unstable and unfavorable because it does not allow farmers to produce twice a year. Northern region in contrast, with its unimodal rainfall pattern (Djossou et al., 2017), allows farmers to produce maize twice. However, northern regions suffer most from high rainfall variability and drought. Yabi and Afouda, (2012) observed a higher frequency of extreme rainfall deficit years (most of them belong to 1970s and 1980s) than in the southern region of the country. And similarly, Agbossou et al., (2012) noted a high probability of succession of drought spells more pronounced in this region from 1971 to 1990, and stated that this may partly explain the decline in maize production during that period.

In addition to observed change in climate trend, impact of future climate projections on maize production will exhibit different spatial distribution. Average maize yield decline (loss of 3-20% in the future) is projected in most areas of sub-Sahara Africa because of reduction in the rain-growing season (Waha et al., 2013). An increase of 1°C would cause a reduction of 65% of harvested maize in some regions (Lobell et al., 2011). In Benin, climate change is expected to decrease yield by 0.9 t ha^{-1} as a result of temperature increases and erratic rainfall (Jones and Thornton, 2003). These abiotic factors are often compounded with biotic stresses such as diseases, pests and weeds, and low varietal potential, leading thereby to low maize yield (Shiferaw et al., 2011).

1.1.3.2. Potentials of improved water management for dry season crop production

In many parts of the world, water management practices such as deficit irrigation and supplementary irrigation are adopted to face the lack of water for crop production (Ali et al., 2017; Haghverdi et al., 2019). The success of these practices implies an available water source nearby the farm either to apply throughout the cropping season or in time of drought spells within the cropping season.

In West African countries in general, there is enough surface water resources for crop production. The region has a flow of 7000 m^3 of water per second in dry season

(Blein et al., 2008). The annual surface water of the region are estimated to 1 011.8 milliard of m^3 (FAO, 2006), out of which less than 2% are mobilized for crop production. This can be explain by a lack of science-based technology that would improve water use efficiency regarding the context of seasonal water availability (UNCTAD, 2011).

With a vast hydrologic network (Volta, Niger, Ouémé, and Mono/Couffo), yet, underexploited, Benin country offers resources to produce in dry seasons. Meanwhile, few if not none of the farmers in Benin make use of the existing opportunities for irrigation of maize in dry seasons. This study is trying to provide an answer to the question: How can food insecurity be reduced using appropriate water management such as supplemental irrigation and deficit irrigation for maize production in Benin?

1.1.4. State of knowledge

Regulated deficit irrigation (RDI) has been investigated for its potential to increase or maintain crop yield with less water (Molden et al., 2010). It is a practice whereby a crop receives an amount of water below the full requirement for its optimal growth in order to increase WUE. A variant of RDI is the stage-based deficit irrigation through which, a timely application of water to the crop, based on growth stages water requirements can substantially increase irrigation efficiency and water productivity (Molden et al., 2003; Zwart and Bastiaanssen, 2004). Stage-based deficit irrigation relies on the principle that plant response to water stress varies with growth stages, and that less water applied to plant at water stress tolerant stages may not cause significant reduction of primary productivity (Chai et al., 2016). For this reason, a knowledge of the sensitive growth stages, and of water requirements at each growth stage is a prerequisite (Fereres and Soriano, 2006). The sensitivity of a plant growth stage to water stress can be affected by many factors, including climatic conditions, crop species and cultivars, agronomic management practices, among others (Chai et al., 2016). Various studies pointed out the reproductive stage as the most sensitive to water stress in major food crops (Gheysari et al., 2017; Rudnick et al., 2017).

One of the obvious benefit that stems from the practice of deficit irrigation is the increase of WUE. This observation remains the same for all growth stage, since less water is lost through soil evaporation. If WUE always increases, the case is different for yield (Chai et al., 2016). Response of crop yield under RDI varies more with the stage at which the deficit has occurred (Fereres and Soriano, 2006). Similarly, for cereal crops, such as sorghum, wheat, subjected to RDI at the reproductive stage, yield is always reduced (García Del Moral, 2003). For example, a short duration of water deficit during tasselling stages in maize (*Zea mays*) reduced biomass production by 30 % and grain yield by up to 40 % (Çakir, 2004). The vegetative stage however makes an increase of crop yield possible depending on the timing and magnitude of water stress (Cui et al., 2009). But especially for maize crop, controversial results are reported, according to which grain yield either increases or decreases. A mild water deficit of 17.48% in PR31P41 maize cultivar at the vegetative stage resulted in 14% reduction of grain yield (Kuşçu and Demir, 2012). Around the same magnitude of water stress in Pioneer brand 3377 cultivar, 9% of yield was reduced (Çakir, 2004). 80% of water deficit caused up to 90% reduction of yield in McCurdy 84AA maize cultivar (Bennett et al., 1989), suggesting that the more water stress increases, the more yield reduces. On the other side, Domínguez et al., (2012) found out that deficit irrigation applied during the vegetative stage increased maize grain yield by 10 to 20 % compared to the stress applied during the whole growth cycle. A study conducted by Eck, (1984) showed that 17.2 % of deficit at the vegetative stage resulted in 5.3 % increase in maize grain yield (variety Pionner 3184) compared to the optimal treatment. More recently, 16.4 % and 21.5% of water deficit in vegetative stage in RH-240 maize variety resulted respectively in 2.9% and 2.3% increase of grain yield (Ayana, 2011). These results reveal a variability in grain yield response to water stress which is due to difference in crop cultivar (under same magnitude of water stress, and same growth stage), and other biotic and abiotic factors non apparent in the given studies. One question that arises then is what other factors may influence crop response to water stress?

Maize response to water stress can be affected by compounding factors, being biotic or abiotic, including soil fertility and water management, climate, and crop genetic. Three macro-nutrients (N, P, K) are essential to plant. With regards to soil fertility, nitrogen (N) is the most limiting fertilizer element as plant require large quantities for its production (Ohyama, 2010). N intervenes in the establishment of leaf photosynthesis, and in the reproductive development. Phosphorus (P) is one of the vital soil component that promotes root growth (Mollier and Pellerin, 1999). P also assists in osmoregulation of cells, helps in opening and closing of stomata, which regulates the exchange of water vapour, oxygen and carbon dioxide. As a macronutrient, potassium (K) is associated with movement of water, nutrients and carbohydrates in plant tissue (Ali et al., 2018). K is involved with enzyme activation, which affects the production of adenosine triphosphate (ATP), in regulation of the rate of photosynthesis (Aslam et al., 2013; Prajapati and Modi, 2012). K also plays a great role in cell expansion and maintains the turgor pressure of plant (Wang et al., 2013). It has been demonstrated that deficit irrigation improves nutrient use efficiency in crop. For example, alternate partial root-zone irrigation in maize enhanced the ratio of N uptake to the N supplied by 16 % compared to fully irrigated control (Li et al., 2007). Similarly, in a maize–wheat rotation study where full irrigation and partial root-zone deficit irrigation were compared in maize, partial root-zone irrigation increased N recovery by 17 % compared to full irrigation (Kirda et al., 2005).

Deficit irrigation (DI) technique offers an opportunity to maintain or increase crop production under water scarce environments (Molden et al., 2010). Through this technique, a timely application of water based on water requirements of growth stages can also substantially increase irrigation efficiency and water productivity (Molden, 2003; Zwart and Bastiaanssen, 2004) by limiting water supply to the sensitive growth stages, and reduce water supplied to drought tolerant growth stages. In most cases, DI has been more efficient than rainfed and full irrigation (FI). Experimental studies showed that well-planned deficit irrigation increased wheat yield by 1.6 t ha^{-1} (Ali et al., 2007) and doubled water productivity compared to rain-fed and fully irrigated crops (Kang et al., 2000; Zhang et al., 2004). Quinoa yield has been maintained with excellent grain size and water productivity doubled under DI (Geerts et al., 2008 a, b). Similar results have been observed for other crops such as groundnut (Nautiyal et al., 2002), garlic (Fabeiro et al., 2003), sugar beet (Kirda et al., 1999), etc. Unlike the precedent crops, reports on maize responses to DI differentiated by phonological stages are unsteady. A study conducted by Kang et al., (2000), revealed that water deficit at seedling stage, plus a further mild soil drying (55% of field capacity) at stem-elongation stage is an optimum irrigation method for maize, as grain yield hasn't been significantly reduced. Meanwhile, Pandey et al, (2000), observed a reduction of maize grain yield from 11.1 to 52% under deficit irrigation during the vegetative period. Nevertheless, that reduction was proportional to the duration of deficit irrigation. Furthermore, Çakir (2004) observed that DI in maize during tasseling or ear formation stage resulted in 30 to 40% loss in grain yield. Farré and Faci (2009) concluded that flowering was the most sensitive stage to water deficit, with an average reduction of grain yield of 35.3%, compared to a reduction of 13.5% and 30.5% for the vegetative stage and grain filling and maturity stages, respectively. The observed difference in yield reduction could be attributed to difference in cultivars used, and in fertilizer input.

Studies that investigated maize response to combined fertilizer and irrigation treatments revealed a significant interaction between fertilizer rates and irrigation treatments. Results of a study conducted by Di Paolo and Rinaldi (2008), showed that nitrogen availability amplified irrigation effect. Under combined application of nitrogen fertilizer (100 Kg N ha^{-1}) and deficit irrigation, Mansouri-Far et al., (2010) observed that maize grain yield reduction was higher in reproductive stage (25.4%) compared to the vegetative (2.06). The same observation was valid under combined adequate nitrogen application (200 Kg N ha^{-1}) and water stress, where the yield reduction recorded was 1.9% in vegetative stage, but 26.8% in reproductive stage. This implies that the more fertilizer is applied, the more sensitive is the plant to water stress, requiring adequate water supply for a higher yield. Such interaction between fertilizer and water availability could be more pronounced for the reproductive stage. Consequently, fertilizer amount influences the sensitivity of a crop to water stress at specific growth stage. However, a relevant question that previous studies have not investigated is to what extent fertilizer application influence the sensitivity of maize growth stages to water stress. In other words, at what levels of fertilizer, growth stages will become sensitive to water stress?

In most dry areas where crop production is rainfed, most of the rainwater is lost through evaporation and runoff. In such areas, beside deficit irrigation, supplemental irrigation is also an efficient strategy that is used to increase crop production mainly for improving livelihoods (Oweis and Hachum, 2004). Supplemental irrigation is a strategy whereby water is applied to a rainfed crop in critical stages when rainfall fails to provide essential moisture for the crop growth. Supplemental irrigation can be applied to avoid moisture stress.

This study will attempt to investigate the response of a short cycle of maize variety to supplemental irrigation and to different levels of water stress. This can provide information to enhance strategic decision-making by farmers and policy makers to adapt to unstable rainfall exacerbated by climate change

1.1.5. OBJECTIVES

1.1.5.1. Overall Objective

The general objective of this study is to assess the potential of deficit irrigation and supplemental irrigation in improving maize production systems in sub-humid climate of Benin

1.1.5.2. The specific objectives

(i) Assess the factors explaining the maize response to irrigation water stress

(ii) Assess the potential of supplemental irrigation in improving maize yield productivity

(iii) Assess the potential of irrigation water deficit in improving maize productivity

1.1.6. Research questions

(i) What are the factors explaining the maize response to irrigation water stress

(ii) Can deficit irrigation during dry season be an appropriate water management strategy for improving maize productivity in Benin?

(iii) Can supplemental irrigation be an appropriate water management strategy for improving maize productivity in Benin?

1.1.7. Research hypothesis

This thesis is guided by the main hypothesis given as:

Supplemental irrigation and deficit irrigation can be used as water management strategies for improving maize production in Benin.

Chapter II: Materials and Methods

2.1. Study areas

2.1.1. Presentation of the selected papers for review

Nineteen (19) peer review papers published mainly in English from 1984 to 2015 were selected first based on their title (**Table 2.1**). The title had to indicate that the study was conducted on grain corn or maize in water stress or deficit conditions. Abstracts were then examined to check the application of irrigation water at a specific growth stage (seedling, vegetative, reproductive, maturity). Publications included in this review satisfied the following criteria: (1) they are published peer review journal articles that reported results from experiments; (2) they indicated the fertilizer amount used (at least the N level); (3) Irrigation is applied during at least one specific maize growth stage, and irrigation water amount is given; (4) when different cultivars are studied, the responses are presented separately for each cultivar; (5) when maize is subjected to different levels of nitrogen, studies reported the interactive effect of different nitrogen and water stress levels on maize. From the studies included in this review, we estimated the cultivar cycle by performing a difference between the harvest date and the sowing date in number of days. Results from rainfed experiments were excluded at the end given the few number of observations recorded (14) which would not allow to draw relevant conclusions.

Table 2. 1 : Characteristics of the studies included in the review.

S/N	Authors of Studies	Titles	Sites/Countries	Growth Stages	Number of treatments per growth stage	Data collected	Experimental design	Cultivar Name; cycle (days)
1	Aguilar et al, 2007		Seville/Spain	R	8	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	Short ; 150 Medium; 150 Long;150
2	Bennett et al., 1989		Faisalabad/ Florida	V	4	WS, GY, Cult_cycle, N_rate	Split plot design	McCurdy 84AA maize; 125
3	Çakir, 2004		Kirklareli/Turkey	V	3	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	Pioneer_brand_3377; 125
				R	18			
				V&R	10			
4	Di Paolo and Rinaldi, 2012		Chieti/Italy	R	4	WS, GY, Cult_cycle, N_rate	Split plot	corn hybrid Tevere; 130
5	Doto. et al., 2015		Kongoussi/Burkina Faso	R	2	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	Barka; 80
6	Eck, 1984		Bushland/ Texas	V	16	WS, GY, IWUE, Cult_cycle, N_rate	Randomized bloc with split plot	Pioneer 3184; 120
7	Ertek and Kara, 2013		Isparta Province/ Turkey	V&R	2	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	Lumina F1; Na
8	Farré and Faci, 2009		Zaragoza/Spain	V	2	WS, GY, IWUE, Cult_cycle, N_rate	Randomized bloc	Prisma; 125
				R	4			
				V&R	2			
9	Gouranga and		Dhenkanal/Asia	V	3	GY, Cult_cycle,	Split plot	Lalat; 120

	Harsh, 2005			R	2	N_rate		
				V&R	3			
10	Hammad. et al., 2012		Faisalabad/Asia	V&R	4	WS, GY, IWUE, Cult_cycle, N_rate	Split plot with RCBD	Pioneer 31-R-88; 105
11	Huang et al., 2002		Loess Plateau/China	V&R	5	WS, GY, IWUE, Cult_cycle, N_rate	Randomized bloc design	NA; 150
12	Kirda et al., 2005		Adana/ Turkey	V&R	4	WS, GY, IWUE, Cult_cycle, N_rate	Complete randomized bloc design	Sele; 120
13	Kusçu and Osman, 2012		Marmara/Turkey	V	3	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	PR31P41; 120
				R	5			
				V&R	3			
14	Mansouri-Far et al., 2010		Kermanshah/Iran	V	2	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	S.C647;120 T.C647; 120
				R	2			
				V&R	2			
			Tehran/Iran	V	2	WS, GY, IWUE, Cult_cycle, N_rate		S.C647;120 T.C647; 120
				R	2			
				V&R	2			
15	Mekonen A., 2011		Arba Minch State/ Ethiopia	V	3	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	RH-240; 135
				R	2			
				V&R	2			
16	NeSmith and Ritchie, 1992		Kalamazoo/USA	R	2	WS, GY, IWUE, Cult_cycle, N_rate	Complete randomized bloc design	Hybrid Great Lakes 599; 100
17	Osborne et al., 2002		Shelton/Nebraska	V&R	5	WS, GY, IWUE, Cult_cycle, N_rate	Split plot	Pioneer brand hybrid 3489; 90

18	Pandey et al., 2000		Konni/Niger	V	3	WS, GY, IWUE, Cult_cycle, N_rate	Split plot	P3Kollo; 100
				V&R	5			
19	Payero, et al., 2009		North Platte/ Nebraska	R	8	WS, GY, IWUE, Cult_cycle, N_rate	RCBD	Hybrid Kaytar KX-8615Bt; 112

V: Vegetative stage, R: reproductive stage: V&R: Vegetative and reproductive stage; WS: Water stress level: GY: grain yield; IWUE: irrigation water use efficiency; Cult_cycle: cultivar cycle; N_rate: Nitrogen rate; RCBD: randomized complete bloc design; Na: cycle not available.

The growth stages at which water stress was applied in different studies are presented in Table 2.2.

Table 2. 2 : Maize growth stages under deficit irrigation identified through literature review

	Growth Stages (English)	Codes
Emergence	Seedling stage	VE
Vegetative*	Vegetative; early vegetative stage	V
	1-Leaf to 11-leaf	V1 to V11
	2-Leaf	V2
	3-Leaf	V3
	4-Leaf	V4
	5-Leaf	V5
	6-Leaf	V6; start of cob initiation
	7-Leaf	V7
	8-Leaf	V8
	9-Leaf	V9
	10-Leaf	V10
	11-Leaf	V11
	12-Leaf	V12
	14-Leaf	V14
	18-Leaf	V18
Reproductive*	Tassel (ling); tassel initiation	VT
	Silking	R1
	Cob (ear) formation	C
	Blister Kernel	R2
	Milking, early grain filling	R3, G
	Dough	R4
	Beginning dent/Full dent	R4.7/R5.5
Physiological Maturity	From milk stage to physiological maturity	
	Physiological Maturity/Maturity	R6

* Represents individual growth stages (vegetative or reproductive stages) where water is depleted. A third case is considered, whereby water is withheld simultaneously at both vegetative and reproductive stages.

The review came across 178 observations grouped into 19 studies and dispersed in the five continents. **Figure 2.1** shows the locations of the studies included in the review, and displays that the majority of the studies were conducted in Europe.

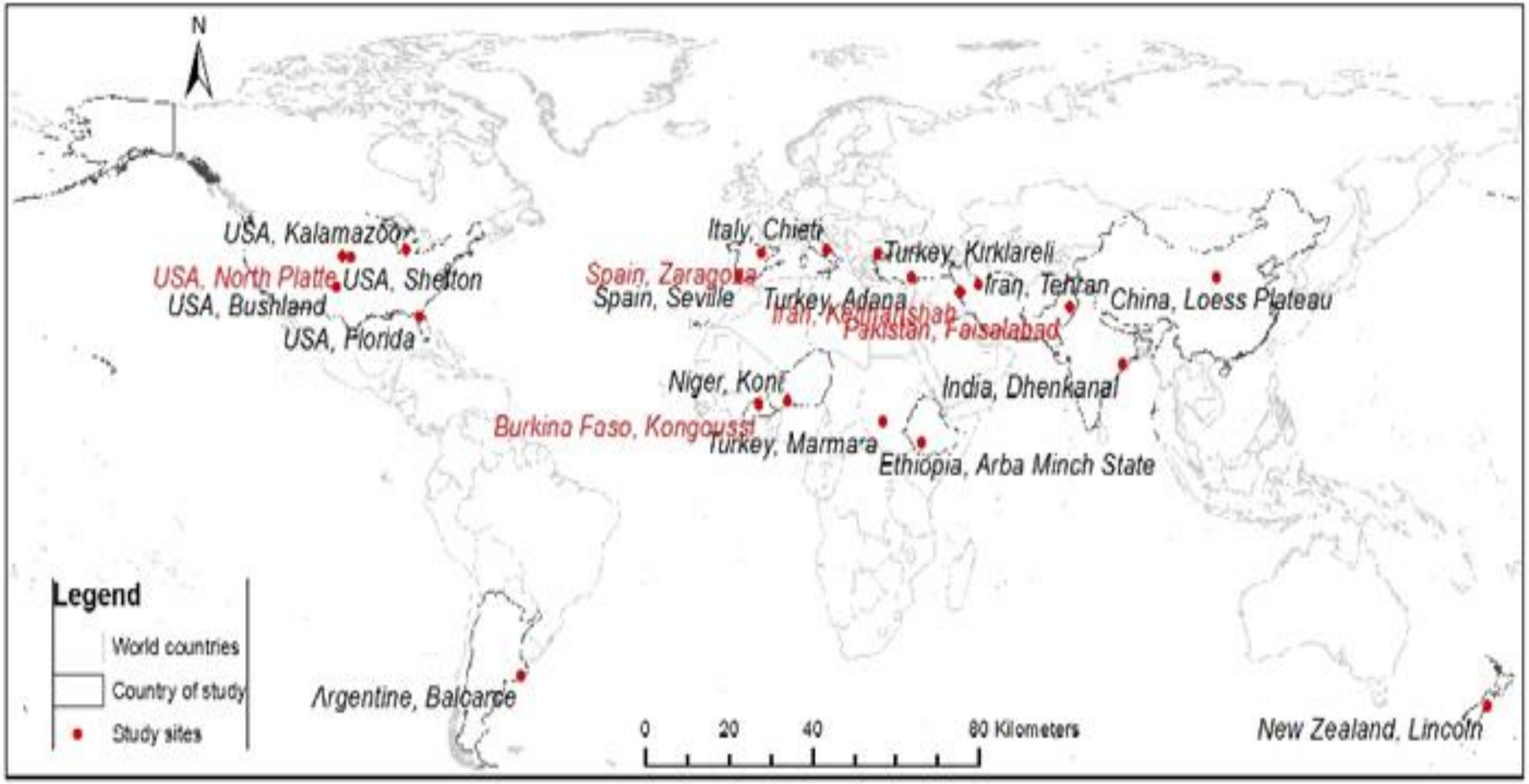


Figure 2. 1: Distribution of locations of studies accounted in this review. Map generated with QGIS version 2.18.4

2.1.2. Description of Experimental Study Site

The experiment was conducted on the Agronomy Faculty farm of the University of Parakou. Experimental site is located at 9°20'08.8" N latitude, and 2°38'54" E Longitude, 347 m a.s.l. Parakou is in the agroecological zone III (Zone vivrière du Sud-Borgou) (MEPN, 2008). According to Koppen-geiger classification, Parakou has a tropical wet and dry climate (Aw), which is marked by a unique rainy season (May-October). The soil is classified as ferruginous tropical soils (Azontonde, 1991). Parakou has on average, an annual rainfall of 1180 mm and a maximum temperature of 33.5°C (CRA-Nord Parakou Climate Database 1980-2018). **Figure 2.2** shows the location of the experimental site.

Maize is the major staple crop produced in Benin on 80% of the total area cultivated for cereals. Maize annual production in Benin increased from 221,666 tons in 1968 to 1.45 million tons in 2017 growing at an average annual rate of 5.08 % (FAOSTAT, 2017)

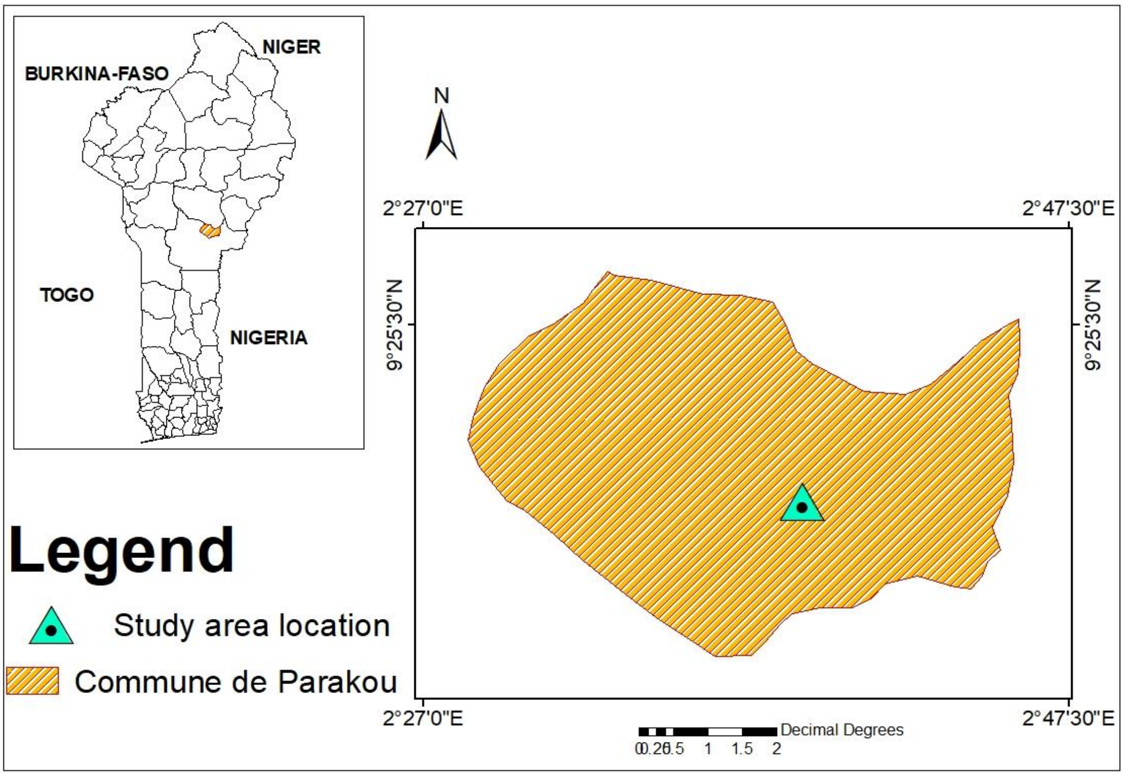


Figure 2. 2 : Location of Study Area

2.2. Materials and Methods

2.2.1. Data extraction from reviewed papers

The observations were extracted from the experiments conducted exclusively in irrigated conditions. Results from rainfed experiments were excluded at the end given the small number of observations recorded (14) which would not allow to draw relevant conclusions.

Data points were extracted both from tables and figures. When results were presented in figures, they were digitized using WebPlot Digitizer version 3.8 in order to easily identify points' values. The total data points before averaging across replicates under the same water stress levels and growth stages was 653. After averaging, and removing missing data, the number of observations that underwent statistical analysis was 150 composed of 37 for the vegetative stage (VS), 59 for the reproductive stage (RS) and 54 for the vegetative and reproductive stage (VRS).

2.2.2. Computation of decision variables for review

The studies considered in this review (Table 2.1) revealed that water was withheld either in vegetative or reproductive stage, or in both vegetative and reproductive stages. The dependent variables studied are the percentage of grain yield reduction (equation 1), the percentage of variation of water productivity (equation 2), under water stress compared to optimal water levels. For the purpose of this study, a water stress index (percentage) has been defined as the ratio of the difference between optimal irrigation water and water under stress conditions, over optimal irrigation water (Equation 3). Only treatments where plots are irrigated outside rainfall were considered.

$$\%\mathbf{Grain\ Yield}_{\mathbf{reduction}} = \frac{(Y_{Opt} - Y_{Str}) * 100}{Y_{Opt}} \tag{1}$$

$$\%\mathbf{IWUE}_{\mathbf{variation}} = \frac{(IWUE_{Str} - IWUE_{Opt}) * 100}{IWUE_{Opt}} \tag{2}$$

$$\%\mathbf{Water\ deficit} = \frac{(I_{Opt} - I_{Str}) * 100}{I_{Opt}} \tag{3}$$

Where Y, is the yield, N, the nitrogen amount, IWUE, the water use efficiency, I, the irrigation water applied. *Opt* indicates optimal treatment where full irrigation water is applied, *Str* refers to treatments that received deficit irrigation water, and c, the control treatment. Only the amount of water applied to the optimal and stressed treatments was recorded in order to compute the water stress index.

In equation (1), a positive result would indicate a reduction of grain yield in the given treatment compared to the control. In equation (2), a positive result would imply that more grain yield is achieved per unit of irrigation water and that a certain amount of water is saved, while a negative value would indicate that less yield is achieved per unit water in stressed treatment compared to optimal treatment. Afterwards, we used grain yield percentage (GYP), IWUE and WD to refer to $\%\mathbf{Grain\ Yield_{reduction}}$, $\%\mathbf{IWUE_{variation}}$, and $\%\mathbf{Water\ deficit}$ respectively.

2.2.3. Experimental Design

Two types of experiment have been conducted. The first type was supplemental irrigation, and was conducted twice in 2018 and 2019. The second type of experiment was conducted in 2019 under deficit irrigation. **Figure 2.3** summarizes all the experiments in relation to the dry and rainy seasons. The experiments under supplemental irrigation were conducted using a randomized complete block design (**Figure 2.4**), with four (04) fertilizer levels and three (03) replications. All treatments were given equal depths of supplemental irrigation within each year. The fertilizer levels where adopted from Tovihoundji et al., 2017, and consisted of the rates : (**F_0**) no fertilizer ; (**F_1**) 2 g of $NPK_{15-15-15}$ hill^{-1}at 15 DAS +1 g urea (46%N) hill^{-1} at 45 DAS; (**F_2**) 4 g of $NPK_{15-15-15}$ hill^{-1}at 15 DAS + 2 g urea (46%N) hill^{-1} at 45 DAS; and (**F_3**) 6.4 g of $NPK_{15-15-15}$ hill^{-1} + 3.2 g urea hill^{-1} at 45 DAS. These rates are equivalent to 23.8 kg N ha^{-1}, 4.1 kg P ha^{-1}, and 7.8 kg K ha^{-1} for F_1, 38 Kg N ha^{-1}, 6.5 Kg P ha^{-1}, and 12.5 Kg K ha^{-1} for F_2, and 76Kg N ha^{-1}, 13.1 Kg P ha^{-1} + 24.9 Kg K ha^{-1} for F_3 respectively. Sowing and harvesting were done manually.

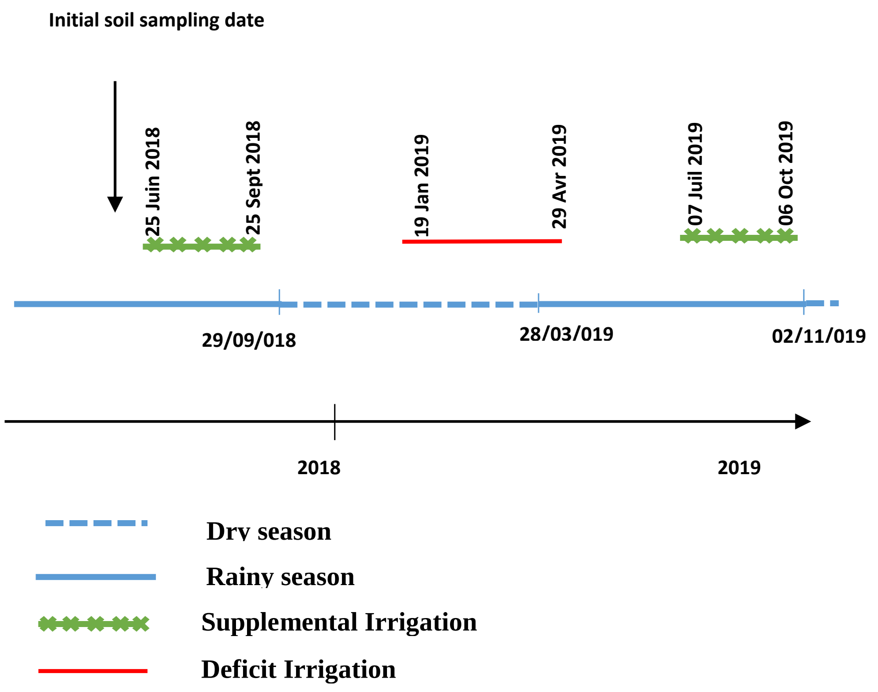


Figure 2. 3: Summary of all experiments conducted in 2018 and 2019 in relation to the dry and rainfall season

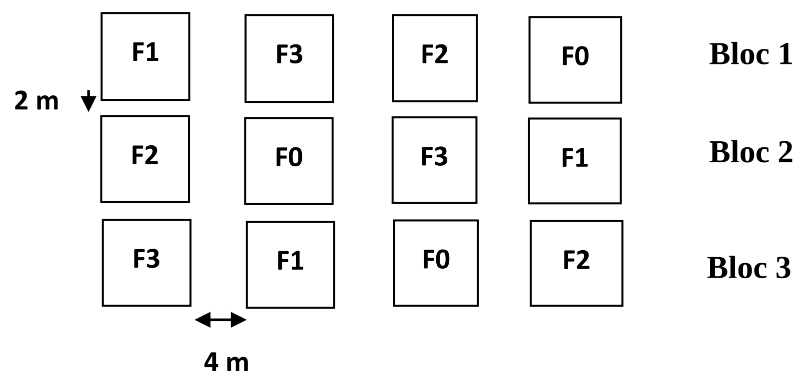


Figure 2. 4: Randomized complete bloc experimental design adopted for experiment under supplemental irrigation. F0: no fertilizer; (F1) 2 g of NPK15-15-15 hill^{-1} +1 g urea (46%N) hill-1; (F2) 4 g of NPK15-15-15 hill-1 + 2 g urea (46%N) hill-1; and (F3) 6.4 g of NPK15-15-15 hill-1 + 3.2 g urea hill-1

Prior to experiment, the land of the experiment site was prepared and disk-plough by a tractor at a depth of 0.2m). Maize variety EVDT-97-STR-W (90 days maturity) was planted on 25th June in 2018 and on 07th July in 2019 under supplemental irrigation. In both years, maize was sown at the same density of 62500 plants ha^{-1}. Each plot was designed as 4.6 m x 3 m and had a total area of 13.8. Sowing was done at a spacing was 0.80m x 0.40m, on six rows per plot. Sowing took place manually in both years in rainfall seasons, and after the cumulative rainfall amount exceeded 20mm. Seedling were thinned to 2 plant hill^{-1} two weeks after sowing. Weeding took place 15 and 30 DAS (days after sowing), and plots were ridged immediately after urea application at 45DAS. Harvest was done manually on 25th September 2018 and on 29th April 2019 respectively for the 2018 and 2019 experiment

The experiment under deficit irrigation took place from 19 January to 21^{rst} April 2019. Maize was irrigated manually, using watering cans of 11 litres of capacity (**Figure 2.5**). Since good germination and earlier crop growth are a prerequisite to observe water stress effect during subsequent crop life stages, water stress was not applied during the emergence stage which lasted for 5 days. Water deficit was applied at the vegetative growth stage of the crop (from 31 days to 51 days after sowing), which corresponds to the period from the 11-Leaf to the 19-Leaf in the optimal treatment. The experimental site had no slope, and we assumed that percolation was minimal from one treatment to the other.

Figure 2. 5: Manual irrigation of maize in dry season

The experimental design was a randomized complete block design (RCBD) with four water stress levels as shown in **Figure 2.6** : (i) Optimal irrigation with no stress (D0), (ii) DI at 25%ETc (D25), (iii) DI at 50%ETc (D50), and (iv) DI at 75%ETc (D75) of maize evapotranspiration, replicated three times. Recommended rates of fertilizer was given to the crop at 200 kg NPK (15-15-15) ha^{-1} + 100 kg of urea, which was equivalent to 76 kg N ha^{-1}, 13.1 kg P ha^{-1}, and 24.9 kg K ha^{-1}, following the farmers practices.

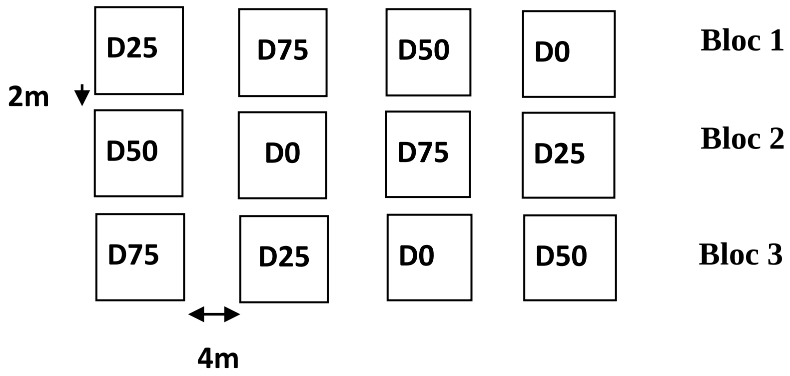


Figure 2. 6: Randomized complete bloc design adopted for deficit irrigation experiment

2.2.4. Field data collection

2.2.4.1. Estimation of Irrigation depths

For the experiment conducted under deficit irrigation, irrigation was optimal from sowing to 30 DAS. Water stress was applied from 31 DAS to 51 DAS based on daily crop water requirement (ETc). ET_c was estimated using Cropwat (V 8.0), which is based on Penman Montheit for the computation of the reference evapotranspiration, ET_o (Allen, 1998). Reference evapotranspiration was therefore estimated with Climwat (V 2.0).

2.2.4.2. Maize growth parameters measured

- Crop height, number of leaves and Leaf Area Index (LAI)

During all experiments, growth parameters (Leaf Area Index, number of leaves, and height) were taken on three plants within each plot, every 3 days during the vegetative growth stage. Leaf area index was monitored by computing the ratio of the sum of all leaf area of a plant over the surface occupied by that plant (80*40 cm^2) (Watson, 1952). Leaf length was measured from the leaf collar to the leaf tip, and leaf width was taken at the largest width (**Figure 2.7**),

$$LAI = \sum_{1}^{n} L * l * k / Surface\ area$$

L is the length of the leave, l, the maximum width, and k, a coefficient of conversion, chosen as 0.75.

Figure 2. 7: Measurement of leaf length (left figure) and width (right figure) at the vegetative stage for all treatments and experiments

- **Temporal dry above ground biomass**

Within individual plot, 2 plants from the same hill were selected every nine days for estimating temporal stover yield. The fresh weight of the two plants was taken, and they were dried in oven for three (03) days at 65°C. The total dry matter of a given day was estimated using the formula:

$$Stv\_yield = \frac{10000 * FW\_stv * DM}{HA}$$

Where:

- Stv_yield is stover yield in kg/m^2;
- FW is the fresh weight of the stover yield harvested in each plot (kg/m^2);
- DM is the dry matter percent of the sample stover.
- HA is the harvested area in m^2, converted in ha.

- **Stover yield at harvest**

At harvest, three inner rows, for a total of 72 plants, were selected for estimating maize grain yield. The total number of plants followed with the number of plants bearing at least one ear were counted. All the plants were cut down and the ears were despathed to bring out the cobs. The fresh weight of the stover, including the leaves, the stalk, the panicles, the spathes and the silks was taken. Then, a sample was made out f it, consisting of a proportional combination of each part. The fresh weight of the sample was measured, and the sample was taken to an oven under

65°C for 3 days. At the end, the dry weight was taken, and the total stover yield per hectare was estimated using the formula:

$$\text{Stv\_yield} = \frac{10000 * FW\_stv * DM}{HA}$$

Where:

- Stv_yield is stover yield in kg/m^2;
- FW is the fresh weight of the stover yield harvested in each plot (kg/m^2);
- DM is the dry matter percent of the sample stover.
- HA is the harvested area in m^2, converted in ha.

- **Grain yield at harvest**

The total number of cobs harvested was counted, and the fresh weight was taken immediately on the field. A sample of the cobs made of 10 cobs of different size was assembled. The fresh weigh of the sample of cobs was taken, and then dried in an oven for three (3) days under 65°C. at the end, the dry weight of the cob sample was measured and the total grain yield per hectare was estimated as follow:

$$Gr\_yield = \frac{10000 * FW\_gr * DM * N}{HA}$$

Where:

- Gr_yield is the grain yield in Kg ha^{-1}
- FW_gr is the total fresh weigh of the cobs harvested in Kg
- DM, is the dry matter of the sample of cob
- N is the ratio of the dry weight of grain obtained after shelling, over the total weight of the sample of cob
- HA is the harvested area, in m^2, converted in ha.

- **Water use efficiencies**

Water use efficiency (WUE) and Irrigation water use efficiency (IWUE) were assessed for all treatments as follow:

WUE ($kg\ m^3$) = GY/ $\sum \boldsymbol{ET}$

IWUE = GY/ total irrigation water amount applied

- **Harvest Index**

Harvest index (HI) was computed using the formula:

HI = Grain Yield /Total biomass

2.3. Data Analysis

2.3.1. Review data analysis

Descriptive statistics was used to present the distribution of studies and observation across continents and climatic zones. The classification of studies location by climatic zones was based on the United Nation Environment Programme (UNEP) aridity index, Table 2.3 (UNEP, 1993). Before the application of inferential statistics, the normality of the data was checked and transformation occurred for dataset that did not meet that requirement for all defined variables at each growth stage (Viechtbauer, 2010).

Table 2. 3 : Classification of climatic zones based on UNEP Aridity Index, (UNEP, 1993):

Climate zones	AI = P/ET	Number of Observations
Cold	>0.65	-
Humid	>0.65	11
Dry sub-humid	0.50-0.65	32
Semi-arid	0.20-0.50	99
Arid	0.05-0.20	35
Hyper-arid	<0.05	-

AI: Aridity index; P: Precipitation; ET: Evapotranspiration

We analysed the relationship between water stress levels and climate zones using a simple regression analysis. Aridity indices based on UNEP classification were used as a proxy of climate zones. Likewise, variation of yield loss percentage was assessed using a multiple regression between water stress levels, and aridity index. Furthermore, the best regression model was identified, through a backward regression analysis using the Akaike information criterion (AIC), where other independent variables such as nitrogen rates, and cultivar cycles were added to the regression.

When using simple linear regressions, the slope of the regression was used to assess severity of yield loss percentage or percentage of irrigation water use efficiency under water stress at each growth stage. For the multiple linear regressions, the multiple R-square, the adjusted R-square, and the P-value of the regression model were used to evaluate the performance of the model. The closer the multiple R^2 and adjusted R^2 were to 1, the better the model. The model was significant when p-value was less than 0.05. All analyses were conducted in RStudio. 1.1.456.

2.3.2. Field data analysis

Temporal data collected during maize growing season were analyzed for every day they were taken. One way Anova was run to check significant difference among treatments, and for each date, the Least Square Difference was used to describe the difference among treatments. For stover and grain yield collected at harvest, a one way Anova was used, followed by turkey test to identify the treatment that differs from others. All analyses were run in RStudio, version 1.1.456.

3.1. Distribution, climatic zones and spatial scale of reviewed studies

Most of the studies were carried out in Europe (**Figure 3.1**). In Africa, studies were reported from Niger, Burkina Faso, Soudan and Ethiopia.

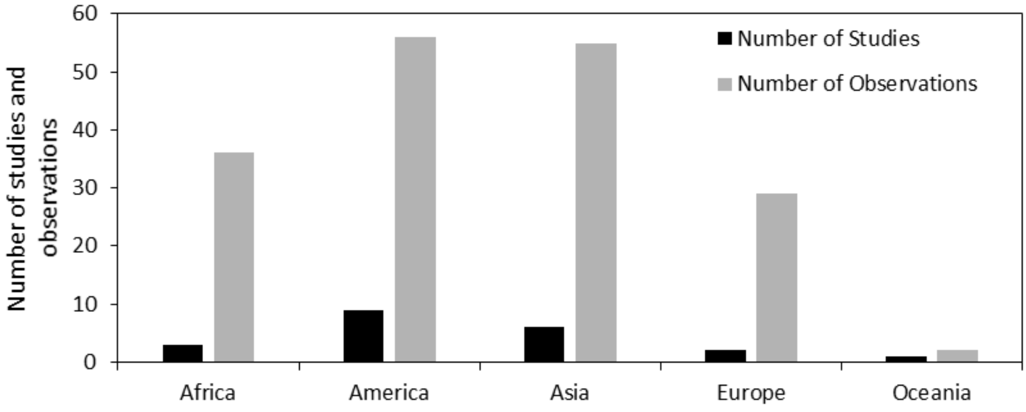


Figure 3. 1: Distribution of studies across continents

All the studies were experimental but 47% of the experiments were conducted on farm (non-controlled environmental conditions) (**Figure 3.2**).

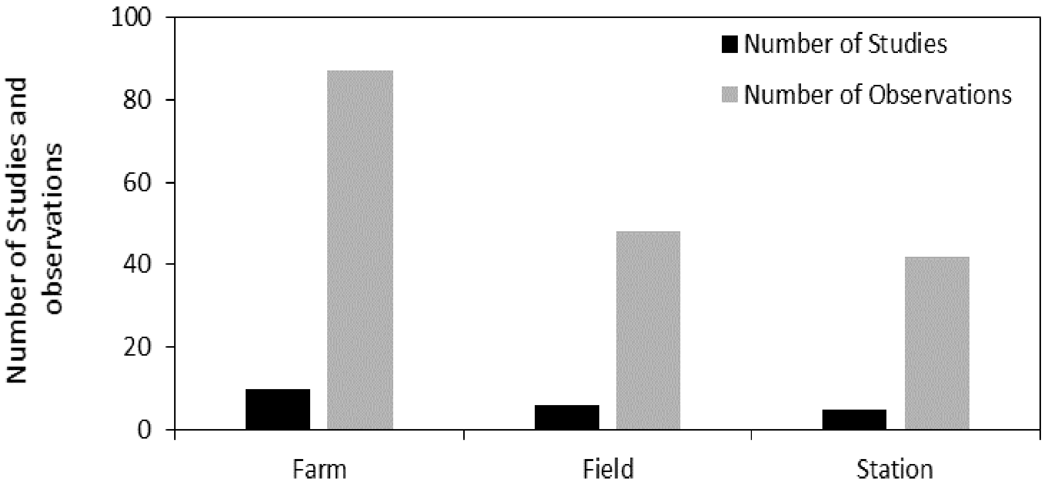


Figure 3. 2: Spatial scales of Studies

3.2. Growth stages and yield parameters in reviewed papers

The review revealed that water stress was applied at specific individual growth stage or at two or more stages simultaneously. Studies where water stress was applied at emergence stage or physiological maturity have been excluded due to lesser number. Therefore, treatments included in the review occurred either during the vegetative stage (VS), or the reproductive stage (RS), or even both the vegetative and the reproductive stage (VRS).

The different yield parameters measured by each study are summarized in Figure 2.4. All studies reported grain yield as crop yield parameters (**Figure 3.3**). But other parameters were reported by 5% of the studies reviewed. The lowest number of observations was recorded for kernel fresh weight, ear fresh weight, number of kernel per row, tasselling percentage and crop growth rate.

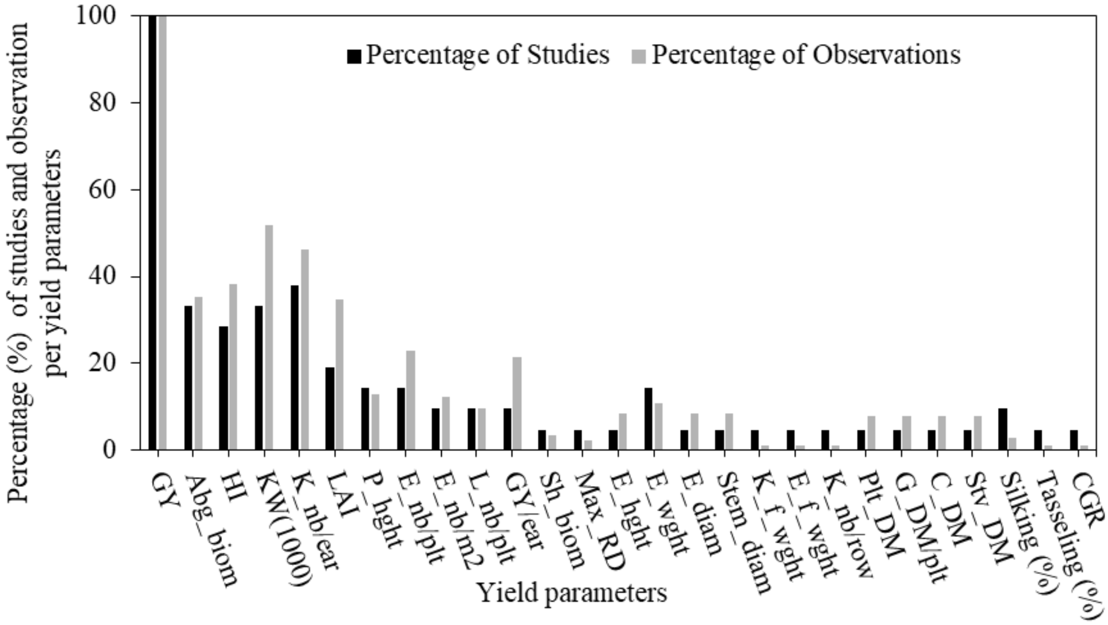


Figure 3. 3: Percentage of studies and observations per yield parameters assessed.

GY: Grain yield ; Abg_biom: Above-ground biomass ; HI: Harvest Index ; KW(1000): 1000 kernel weight ; K_nb/ear: Kernel_number per ear ; LAI: Leaf Area Index ; P_hght: Plant height E_nb/plt: Ear number per plant ; E_nb/m^2: Ear number per m^2 ; L_nb/plt: Leave number per plant ; GY/ear: Grain weight per ear ; Sh_biom: Shoot biomass ; Max_RD: Maximum root depth E_hght: Ear height; E_wght: Ear weight ; E_diam: Ear diameter ; Stem_diam: Stem diameter ; K_f_wght: Kernel fresh weight ; E_f_wght: Ear fresh weight ; K_nb/row: Kernel number per row ; Plt_DM: Plant dry mass ; G_DM/plt: Grain dry mass per plant ; C_DM: Cob dry mass ; Stv_DM: Stover dry mass ; Silking (%): Percentage of silking ; Tasseling (%): Percentage of tasseling ; CGR : Crop growth rate.

3.3. Relationship between climate zones and water stress levels applied

At all growth stages, the more humid the zone, the higher the level of water stress (WD) (**Figure 3.4**). At vegetative stage (VS), water stress levels did not exceed 30% in arid and semi-arid zones, but reached 80% in dry-subhumid zones (DSH). At reproductive stage (RS), the highest water stress level zone was around 60%, 75%, and 80% in arid, semi-arid and subhumid zones respectively.

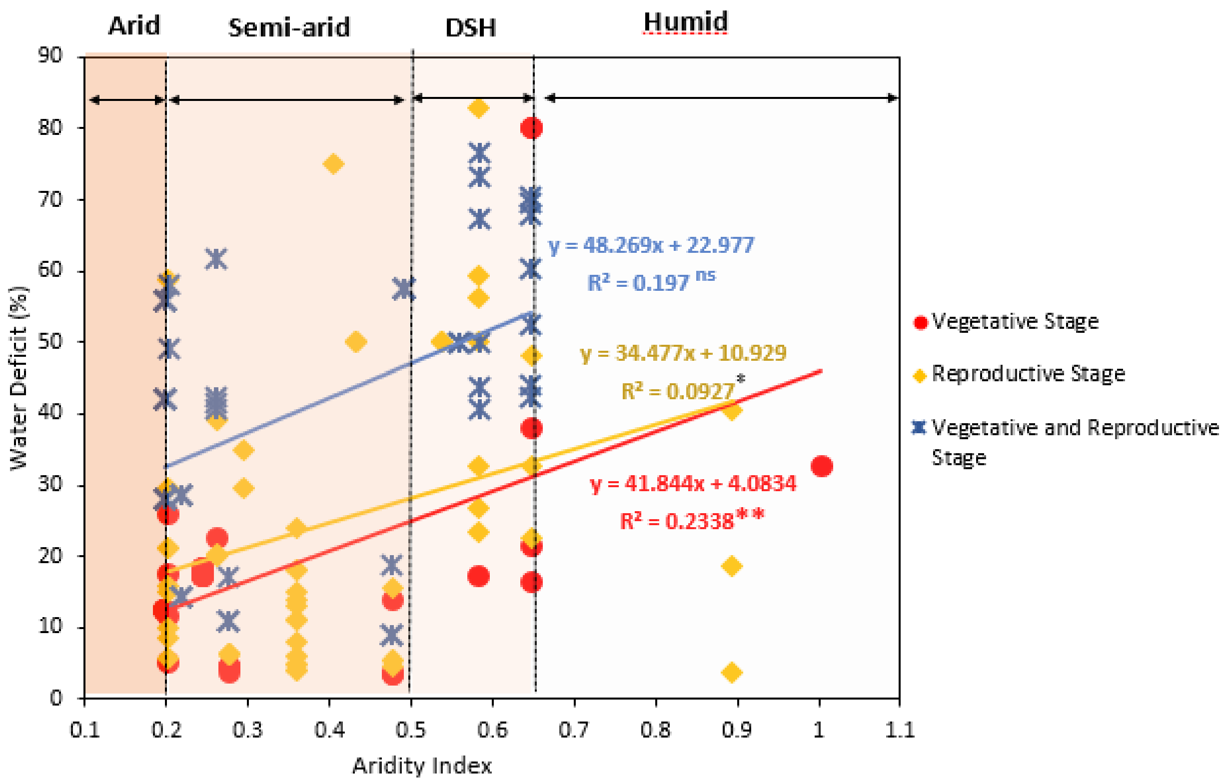


Figure 3. 4: Regression of Water deficit levels in relation to regions Aridity Index

3.4. Maize grain yield loss percentage in relation to water stress levels and climatic zones

3.4.1. Effect of water stress levels on grain yield loss

The backward selection indicated that only water stress had a significant correlation with yield and IWUE variability at all growth stages (**Table 3.1**). As a result, yield loss percentage (GYP) was analyzed mainly as a function of water stress levels (WD). Positive relationship was observed between yield loss percentage and percentage of water stress at all growth stages (**Figure 3.5 A, B & C**). However, the trends varied with growth stages as indicated by the slope of the linear curves. The slope of the regression is high for RS (0.43) and low for VS (0.15) (**Figure 3.5** A, B & C). Water stress level accounted only for 4% of the variance in grain yield when the stress was applied at the VS (**Figure 3.5** A). Whereas, 23% and 15% of the variance was explained by the percentage of water stress when this occurred at the RS and VRS, respectively (**Figure 3.5 B and C**).

Table 3. 1: Multiple linear regression model of GYP and IWUE for different treatments across studies

	Percentage of Grain yield reduction		Percentage of Irrigation water use Efficiency reduction	
	Vegetative Stage			
	Estimates	Std. Error	Estimates	Std error
Intercept	-4.16	3.60	-11.98	4.12 **
Water Deficit Percentage	0.86	0.12 ***	1.42	0.21 ***
Nitrogen Rates	0.0005	0.018	0.006	0.015
Adjusted R^2: 0.59; Multiple R^2 = 0.62			Adjusted R^2: 0.57; Multiple R^2 = 0.60	
F- statistic = 27.27 on 2 and 34 DF; p-value: 8.60 e-08 < 0.001			F-statistic: 22.86 on 2 and 31 DF, p-value: 7.95 e-07 < 0.001	
	Reproductive Stage			
Intercept	6.77	5.78	-14.50	9.80
Water Deficit Percentage	0.45	0.11 ***	0.68	0.18 ***
Nitrogen Rates	0.02	0.02	-0.02	0.03
Adjusted R^2: 0.22; Multiple R^2 = 0.54			Adjusted R^2: 0.21; Multiple R^2 = 0.24	

F-statistic: 8.573 on 2 and 53 DF, p-value: 0.00059 < 0.001			F-statistic: 8.34 on 2 and 53 DF, p-value: 0.0007 < 0.001	
	Vegetative and reproductive Stage			
Intercept	12.67	5.89 *	-18.81	16.12
Water Deficit Percentage	0.32	0.11 **	0.66	0.29 *
Nitrogen Rates	0.02	0.02	0.11	0.05 *
Adjusted R^2: 0.10; Multiple R^2 = 0.13			Adjusted R^2: 0.09; Multiple R^2 = 0.12	
F-statistic: 4.45 on 2 and 58 DF, p-value: 0.016 < 0.05			F-statistic= 3.88 on 2 and 57 DF, p-value: 0.03 < 0.05	

***: p < 0.001; **: p < 0.01; *: p < 0.05.

Figure 3.5 shows that in VS, 86% of the observations were recorded for water deficit level (WD) below 20%, among which 51% were between 10 and 20% (**Figure 3.5 A**). Under low deficit (20%) in VS, grain yield loss percentage (GYP) varied from 0.5 to 17.5% of optimal yield. But above that range of deficit, GYP up to 70% of optimal yield was reached when WD was around 80%. For RS, 52% and 76% of the observations were below 20% and 40% of deficit, respectively (**Figure 3.5 B**). Under 20% of deficit at RS, GYP was 46%, and could be above 90% when WD was around 80%. Whereas, in VRS, 58% of the observations were recorded above 40% of WD (**Figure 3.5 C**). In the same stage, 0.70 to 30% GYP occurred below 20% of WD. High GYP of 86% were obtained between 20 and 40% of WD.

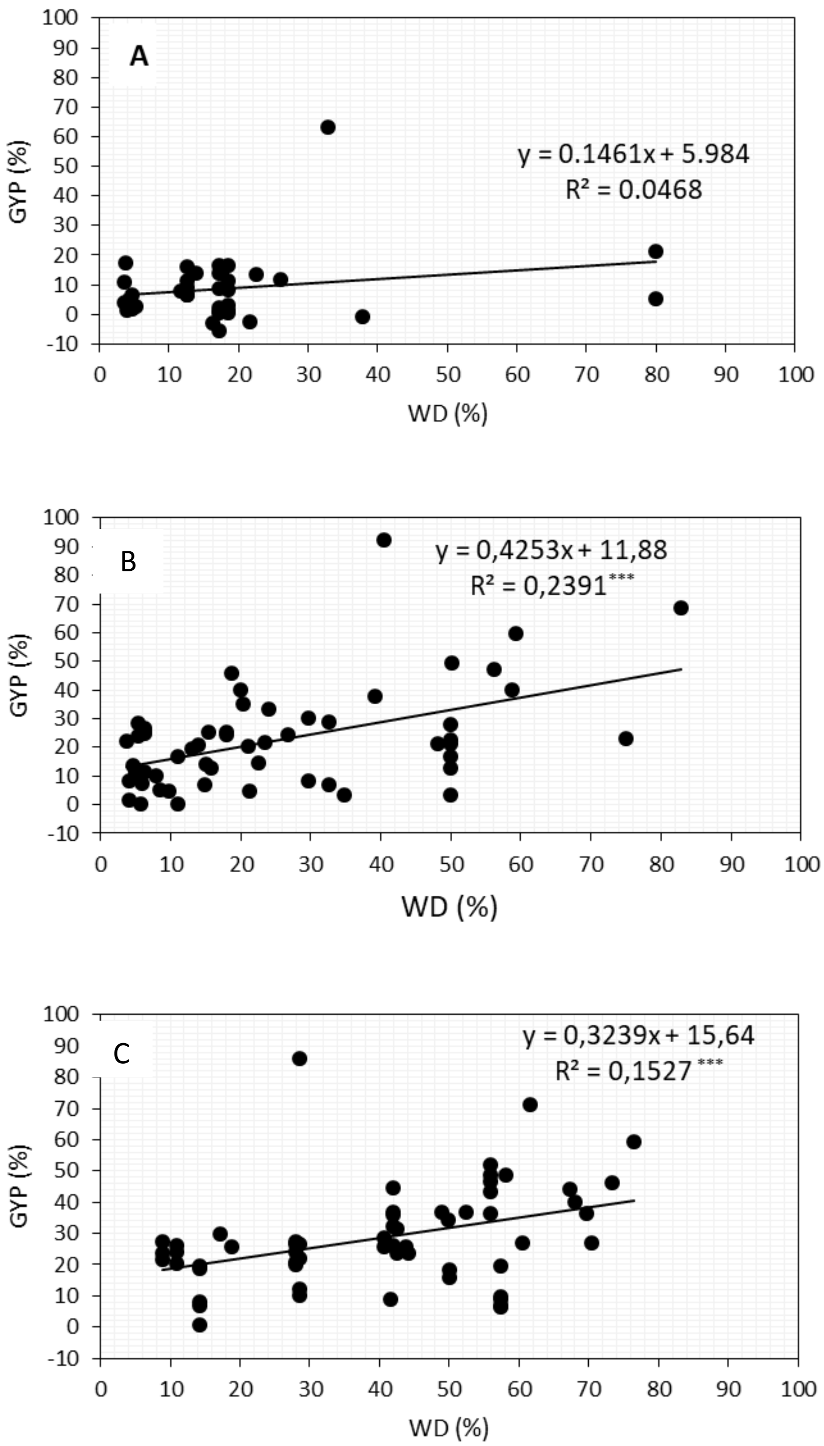


Figure 3. 5 : Trend of maize yield loss under deficit irrigation set at: A) Vegetative stage, B) Reproductive Stage, and C) at vegetative and reproductive stages; ***: $p < 0.001$.

Percentage of grain yield loss (GYP) varied with growth stage ($p<0.05$; Table 2.5). Nitrogen had no significant effect on GYP at all stages (**Table 3.2**). At the VS, GYP was high above 300 kg ha^{-1} (slope = 0.12) while there seemed to be no reduction of grain yield between 200 and 300 kg ha^{-1} of nitrogen (slope = -0.004), (Appendice 1**Erreur ! Source du renvoi introuvable.**). At the RS, negative trend was observed under 100 kg ha^{-1} (slope = -0.07), (Appendice 2). Between 200 and 300 kg ha^{-1}, the slope of the trend was very weak (0.07). The reduction was high at the high rates of nitrogen (above 300 kg ha^{-1}) slope of = 0.72). At the VRS, similar trends were observed. Yield reduction was high above 300 kg ha^{-1} (slope = 0.97; Appendice 3), and very weak when nitrogen rate was between 200 and 300 kg ha^{-1} (slope = 0.17; Appendice 3).

Table 3. 2: Variation of percent of yield loss percent and irrigation water use efficiency percent across maize growth stages

GROWTH STAGES	GYP	IWUE
Vegetative	5.5^{a}	8.9^{ab}
Reproductive	27.0^{b}	4.5^{a}
Vegetative + Reproductive	21.4^{ab}	22.5^{b}
Significance	<2e-16***	**

***: p < 0.001; **: p < 0.01

3.4.2. Simultaneous relation between grain yield loss, water stress level, and climate zones

At VS and RS, the higher the water stress and the more humid the climate, the higher yield loss percentage (**Figure 3.6 A&B**). However at VRS, this observation was partially valid. Yield loss percentage (GYP increased as water stress increased, but decreased as the climate is humid (**Figure 3.6 C**). In Arid zones, yield loss percentage was higher at VRS, and lower at VS. In semi-arid and in subhumid zones, yield loss percentage was lower at VRS.

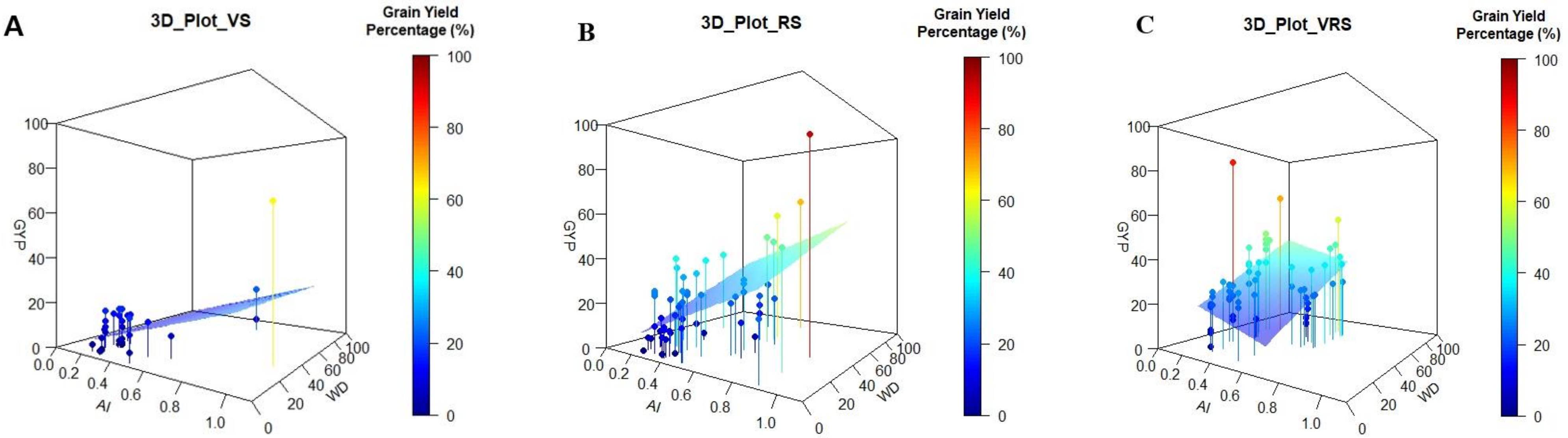


Figure 3. 6: 3D Plot of grain yield loss percentage (GYP) in relation to water deficit levels (WD) and Climatic zones represented by aridity indices (AI) at: A) vegetative stage, B) reproductive stage, and C) vegetative and reproductive stage.

The multiple linear model analysis shows that 58%, 21%, and 0.17% of the variability in yield loss were explained by water stress and nitrogen rates in VS, RS and VRS respectively. GYP was negatively correlated with nitrogen rates at the VS, and the influence of this latter on GYP is quite low at all growth stages. To improve our understanding, we increased the explanatory variables by adding the cultivar maturity length, and/or the climate of the locations (categorical variable) to the multiple linear model regression of GYP. The results (**Table 3.3**) showed that for all growth stages, the multiple R^2 increased from 62% to 90% in VS; and 13 to 33% in VRS. The adjusted R^2 similarly improved in the same range, from 59 to 89% in VS, 22 to 39% in RS, and 10 to 18% in VRS. In VS, only the climate and water has a significant effect on GYP (P-value < 0.05). In RS and VRS stages, the model that performed best is the one considering percentage of water stress, and climate as explanatory variables of GYP.

Table 3. 3: Result of best regression model of GYP and IWUE for different treatments across studies

	Percentage of Grain yield reduction		Percentage of Irrigation water use Efficiency reduction	
	Estimates	Std. Error	Estimates	Std. error
Intercept	9.61	2.00 ***	-14.63	3.76 ***
Water Deficit Percentage			1.21	0.20 ***
Dry-subhumid	-8.82	3.61 *	16.14	5.01 **
Humid	59.50	4.01 ***		
Semi-arid	-2.83	2.40	7.39	3.07 *
Adjusted R^2 =0.89; Multiple R^2 = 0.90			Adjusted R^2 =0.68; Multiple R^2 = 0.71	
F-statistics = 100.5 on 3 and 33 DF; p-value: 2.2e-16 < 0.001			F-statistics = 24.25 on 3 and 30 DF; p-value: 3.65e-08 < 0.001	
Reproductive Stage				
Water Deficit Percentage	0.42	0.11***	0.32	0.17 .
Dry-subhumid	6.08	6.52	23.98	10.45 *
Humid	39.33	9.14***	-45.54	14.66 **
Semi-arid	5.56	5.20	-9.66	8.33
Adjusted R^2 =0.39; Multiple R^2 = 0.44			Adjusted R^2 = 0.46; Multiple R^2 = 0.50	
F-statistics = 10.01 on 4 and 51 DF;			F-statistic: 12.57 on 4	

p-value: 4.66e-06 < 0.001			and 51 DF, p-value: 3.44e-07 < 0.001	
Vegetative and reproductive Stage				
Intercept	18.76	6.84 **	91.90	64.83
Water Deficit Percentage	0.29	0.13 *	0.56	0.42
Dry-subhumid	0.41	5.36	16.44	23.27
Humid	-17.28	6.75 *	51.05	17.98 **
Semi-arid	-2.55	5.55	14.35	14.33
Nitrogen level			0.08	0.05
Cultivar cycle			-1.06	0.51 *
Adjusted R^2 =0.18; Multiple R^2 = 0.23			Adjusted R^2 =0.28; Multiple R^2 = 0.36	
F-statistics = 4.29 on 4 and 56 DF; p-value: 0.004 < 0.01			F-statistics = 4.92 on 6 and 53 DF; p-value: 0.00046 < 0.001	

***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; '.': 0.1

3.4.3. Effect of water stress on irrigation water use efficiency (IWUE)

IWUE varied with growth stage (**Table 3.2**). IWUE increased as water deficit levels (WD) increased irrespective of growth stage. **Figure 3.7 a, b & c** presents positive trends of IWUE as WD increased at the VS, RS and VRS respectively. Increases of IWUE were achieved at all growth stages, but this was more important when WD occurred at both vegetative and reproductive stages (slope = 1.61, **Figure 3.7 a**). The positive trend was weak at the RS (slope = 0.04, **Figure 3.7 b**). 60%, 23% and 50% of the variability of IWUE was explained by water stress at the VS, RS and VRS, respectively.

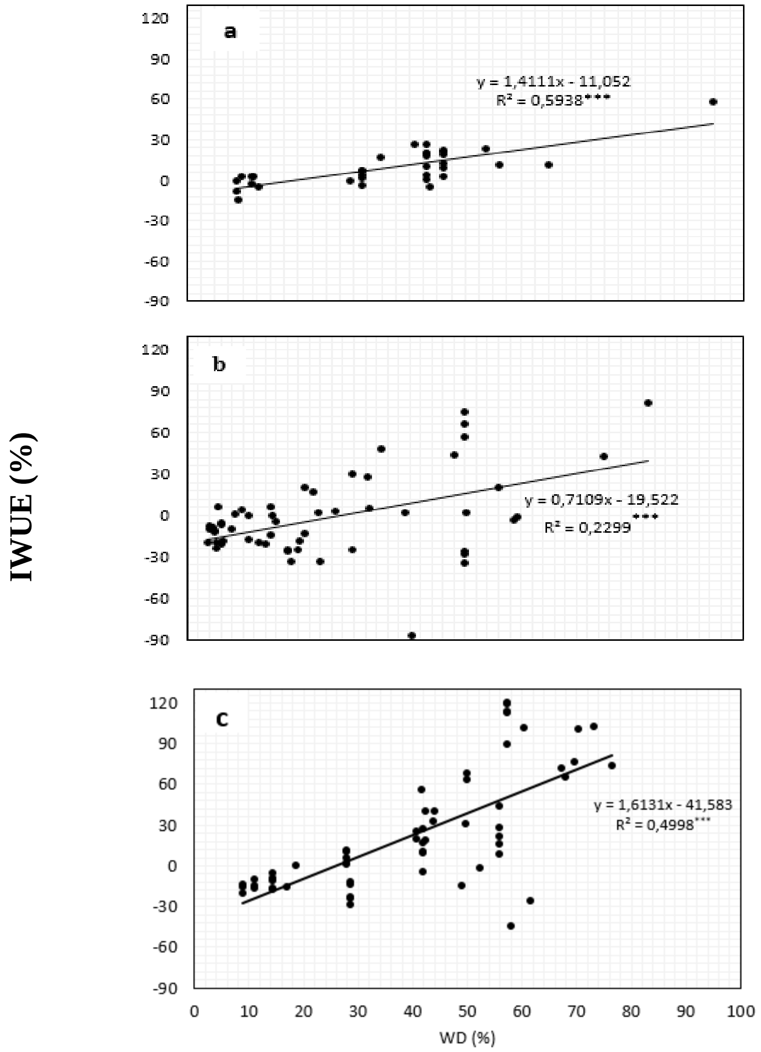


Figure 3. 7: Trend of irrigation water efficiency proportion under deficit irrigation set at: a) Vegetative stage, b) Reproductive Stage, and c) at vegetative and reproductive stages; ***: $p < 0.001$.

Nitrogen rates had no significant effect on IWUE proportion at all stages (**Table 3.3**). At VS and VRS, WUE was high when nitrogen rates was below 100 kg ha^{-1} and low above 300 kg ha^{-1} (Appendice 4 and 6). At RS, WUE was high when nitrogen rate was between 200 and 300 Kg ha^{-1} (Appendice 5) and low between 100 and 200 kg ha^{-1} (Appendice 6).

3.5. Maize production under supplemental irrigation

3.5.1. Soil properties of the experimental field

The texture of the soil was loamy-sand at all layers. **Table 3.4** presents the chemical and textural characteristics of the soil at the experiment site. The soil was sowewhat alkaline at all depths. Organic carbon, total nitrogen levels, phosphorus were higher in the upper layer, but decreased with depth (**Table 3.4**)

Table 3. 4: Initial soil conditions of the Parakou experiment site in Benin

Parameters	0-20cm	20-40	40-100
Soil chemical properties			
pH (H_2O)	7.4	7.6	7.5
Organic carbon (%)	1.07	0.553	0.276
Total N (mg kg^{-1})	595.8	426.4	242.7
Total P (mg kg^{-1})	307.8	176.1	138.9
Total K (%)	0.15	0.15	0.17
NH_4^+ (mg kg^{-1})	26.8	28.9	21.2
NO_3^- (mg kg^{-1})	0.17	0.15	0.16
Bulk density	1.56	1.30	1.48
Electrical Conductivity ($cmol^+$ kg^{-1})	5.62	5.64	3.80
Soil texture			
Sand (%)	77.4	77.8	72.2
Silt (%)	14.5	12.1	13.1
Clay (%)	8.1	10.1	14.6
Texture	Loamy sand		
Soil water retention caracterisitcs			
Soil moisture content at field capacity, cm^3 cm^{-3}	0.1	0.123	0.14

3.5.2. Rainfall distribution patterns during experiments

Figure 3.8 shows that rainfall during the 2018 growing period was 653 mm from 47 rainfall events. Rainfall was unevenly distributed in time, as no rainfall event was recorded from 40 to 50 DAS, and from 50 to 60 DAS. Whereas, these dry periods were important for maize crop flowering.

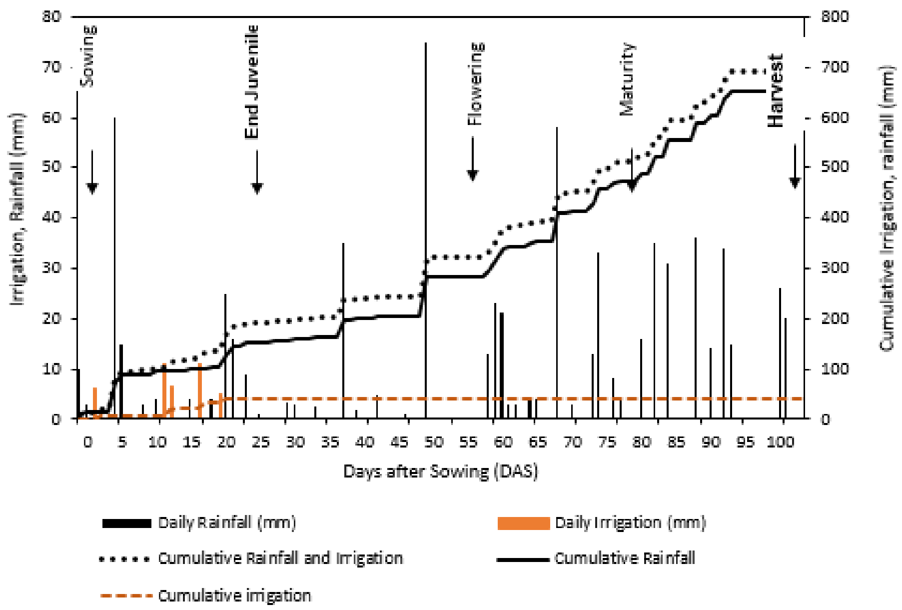


Figure 3. 8: Rainfall, Cumulative rainfall, and irrigation recorded during the experiment conducted under supplemental irrigation, 2018

Figure 3.9 shows that during the 2019 maize growing period under supplemental irrigation, rainfall was 790 mm from 38 rainfall events. Total water applied through irrigation was 71mm.

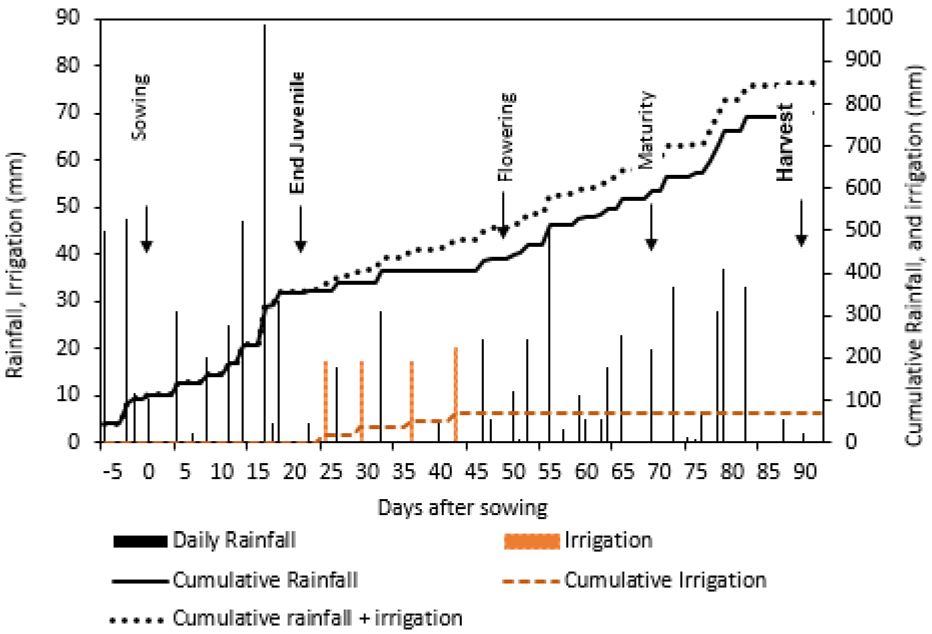


Figure 3. 9: Rainfall distribution during experiment conducted under supplemental irrigation in 2019

3.5.3. Evaluation of Maize growth parameters under supplemental irrigation conditions

The number of leaves, Leaf Area Index (LAI), height, and the temporal stover yield of maize in 2018 are presented in **Figure 3.10**. The maximum number of leaves was observed in F3 treatments (**Figure 3.10 A**). LAI significantly differed between treatments from 27 DAS to 90 DAS and was maximum in F2 treatments from 36 DAS to the end of growing season (**Figure 3.10 B**). Maximum LAI was 1 .1 for F0 treatment whereas it reached 2 for the F3 treatments. There was a significant difference in crop height across treatments from 24 DAS to end of vegetative stage (**Figure 3.10 C**). Crop height was maximum in F3 treatments from 33 DAS to 43 DAS. Stover yield increased with increasing fertilizer rates from 12DAS to 50 DAS, but was higher in F2 treatment from 53 DAS to harvest (**Figure 3.10 D**).

Figure 3.11 shows grain yield and stover yield of maize grown under supplemental irrigation in 2018 across different fertilizer rates. There was a significant difference in grain yield between treatments for with the maximum obtained in F3 treatment. Grain yield was 55%, 21%, and 7% higher in F3 treatment compared to F0, F1, and F2 treatments respectively. Stover yield varied significantly from 2.3 Kg ha^{-1} for unfertilized treatment to 4.4 Kg ha^{-1} for the recommended treatment. Stover yield was 47%, 14%, and 2% higher in F3 compared to F0, F1, and F2, treatments respectively.

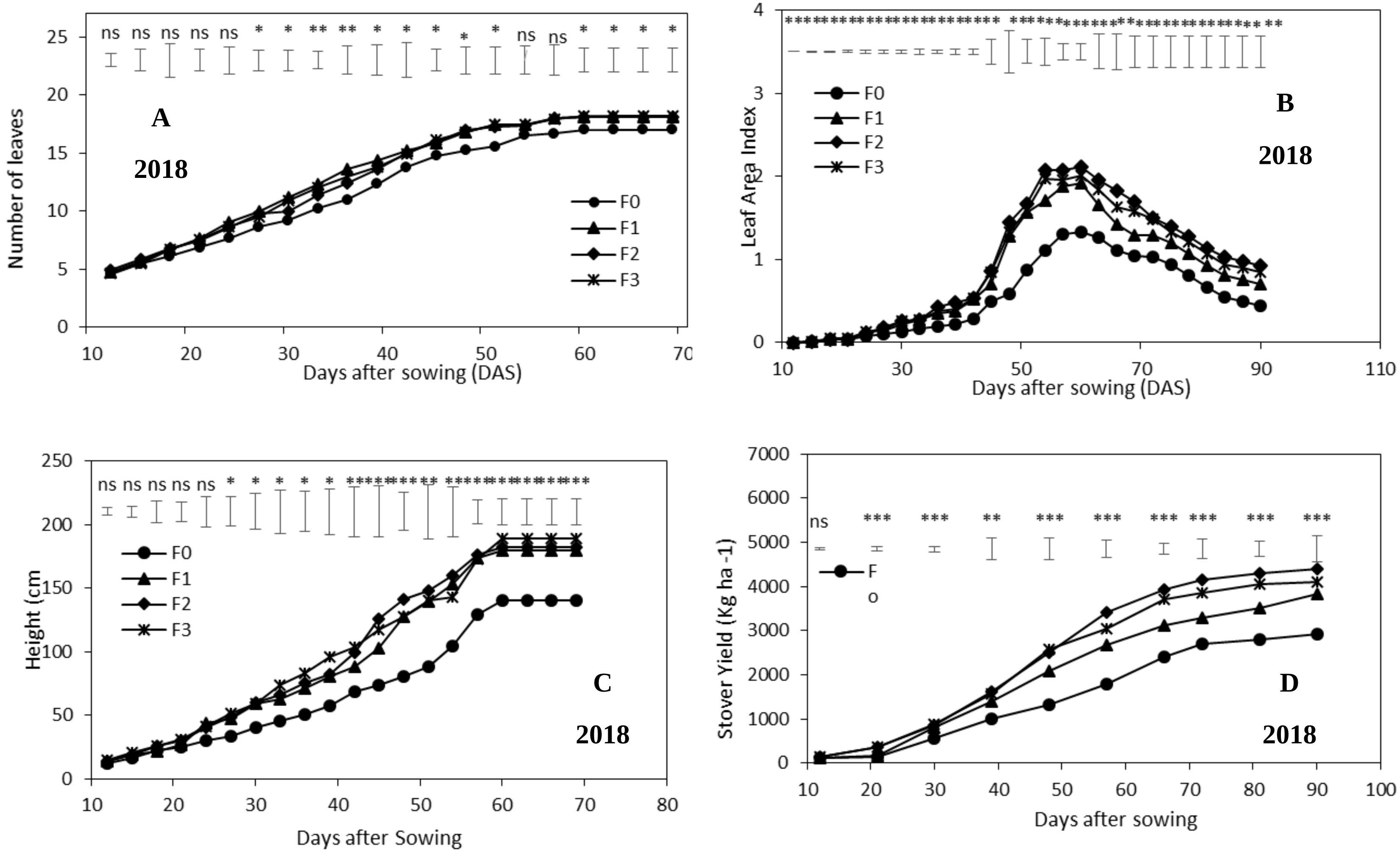
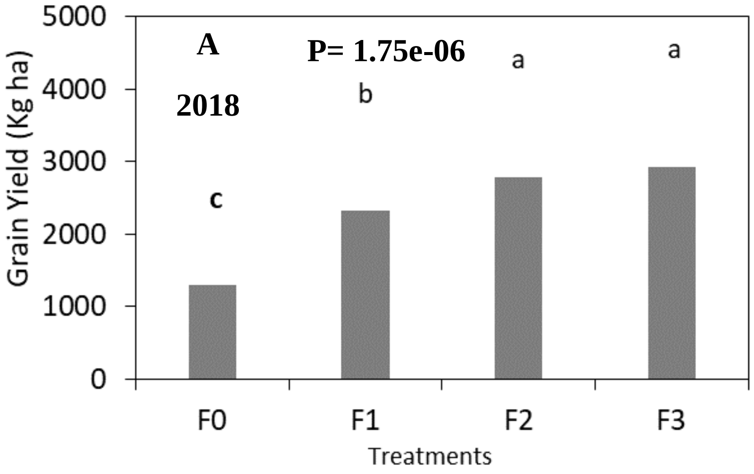


Figure 3. 10: A- Number of leaves; B- Leaf Area Index; C- Height, and D- Temporal stover yield of maize plant under supplemental irrigation, 2018.



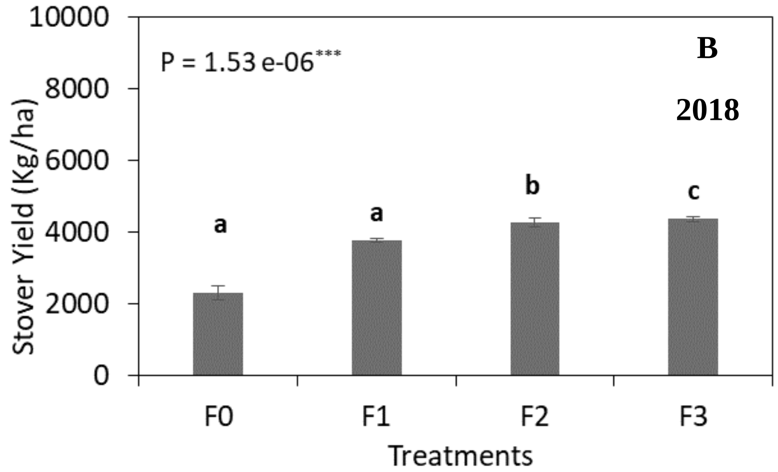


Figure 3. 11: A- Grain yield; and B- Stover yield of maize plant under supplemental irrigation, 2018. Anova results are presented in Appendice 7

Figure 3.12 presents the number of leaves, the LAI, height, and time series stover yield of maize grown under supplemental irrigation in 2019. The results show that generally, the values all the parameters were higher compared to maize growth under supplemental irrigation in 2018. This observtion is remarkable for F3 treatments. LAI significantly differed between treatments from 33 DAS to 90 DAS and was maximum in F3 treatments. Maximum LAI was 1.1 for F0 treatment whereas it reached 2 for the F3 treatments (**Figure 3.12 B**). There was a significant difference in crop height which maximum value vas observed in F3 treatment from 23 DAS. Maize plants reached the same height at the end of the vegetative stage (**Figure 3.12 C**). Time series biomass increased as fertilizer rates increases, from 25 DAS to harvest. During the growing period, the maximum biomass was observed in F3 treatments (**Figure 3.12 D**).

Grain yield and stover yield in 2019 are presented in **Figure 3.13**. Grain yield and stover yield varied significantly across treatments. The values of both parameters were higher in F3 treatments. Grain yield increased by 63%, 16%, and 14% in F3 treatments compared to F0, F1, and F2 respectively. Stover yield increased by 43%, 12%, and 9.1% in treatments F3, compared to treatments F0, F1, and F2 respectively. Anova results for grain yield and stover yield are presented in **Appendice 8**. There was no significant interaction effect of treatments and years on grain yield and stover yield (**Appendice 9**)

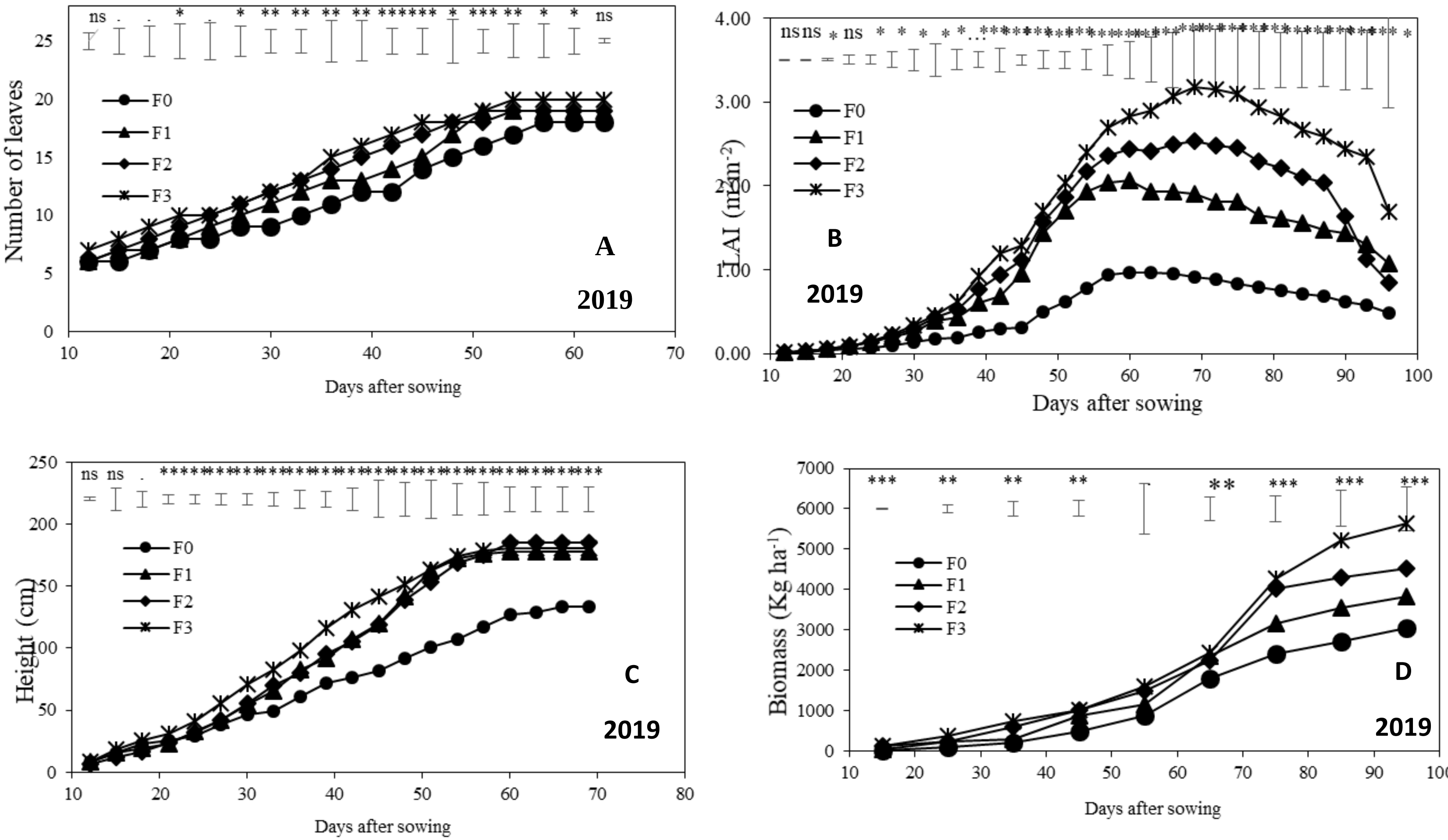


Figure 3. 12 : A- Number of leaves; B- Leaf Area Index; C- Height, and D- Temporal stover yield of maize plant under supplemental irrigation conditions, 2019

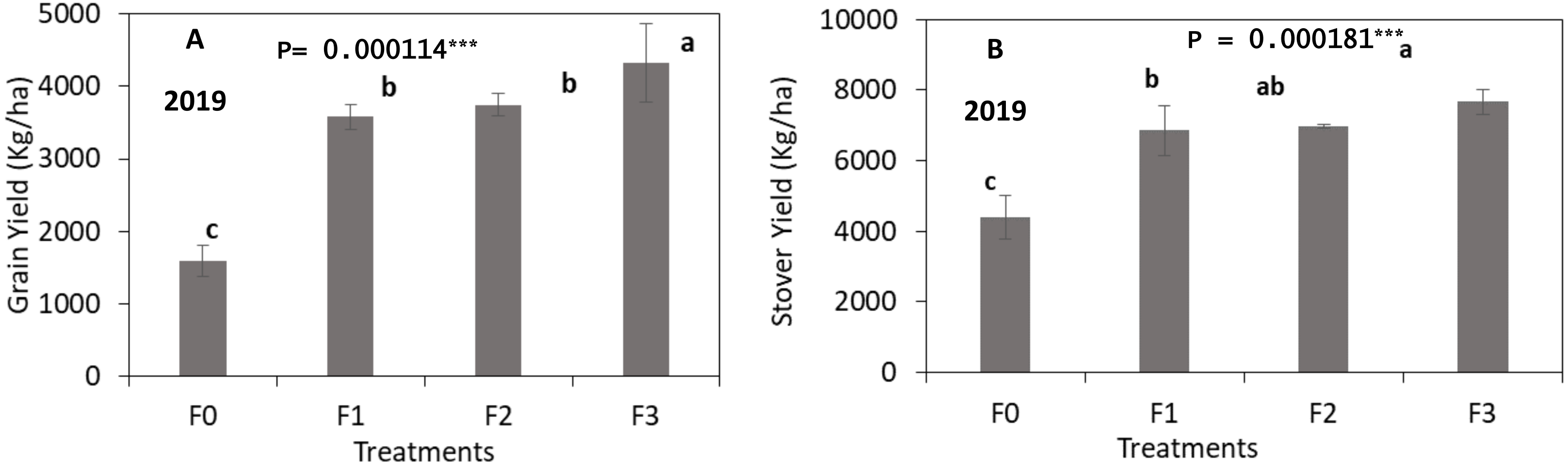


Figure 3. 13: A- Grain yield and B- Stover yield of maize plant under supplemental irrigation, 2019. Anova results are presented in Appendice 8

3.6. Maize production under deficit irrigation

3.6.1. Rainfall distribution and irrigation application

Five main rainfall events were recorded during the cropping season in 2019 The first rainfall (26 mm) event was observed 5 days after sowing (DAS) at emergence of maize shoots, which was observed on 26 January 2019. The second major rainfall (30mm) was recorded about 48 DAS around maize reproductive stage (first tassel appearance in optimal treatments). A cumulative rainfall amount of 38.5mm was recorded during the growing season (**Figure 3.14**).

From sowing to 30 DAS all treatments were fully irrigated to daily maize water needs (ET_c). From 31 DAS to 51 DAS, deficit irrigation was applied with respective reductions percent: 25% ETc reduction, 50% ETc reduction and 75% ETc reduction in D25, D50, and D75 respectively. A total irrigation water of 720.23 mm, 663.51 mm, 621.60 mm and 590.17 mm was applied to the optimal (D0), D25, D50, and D75 treatment respectively (**Figure 3.14**).

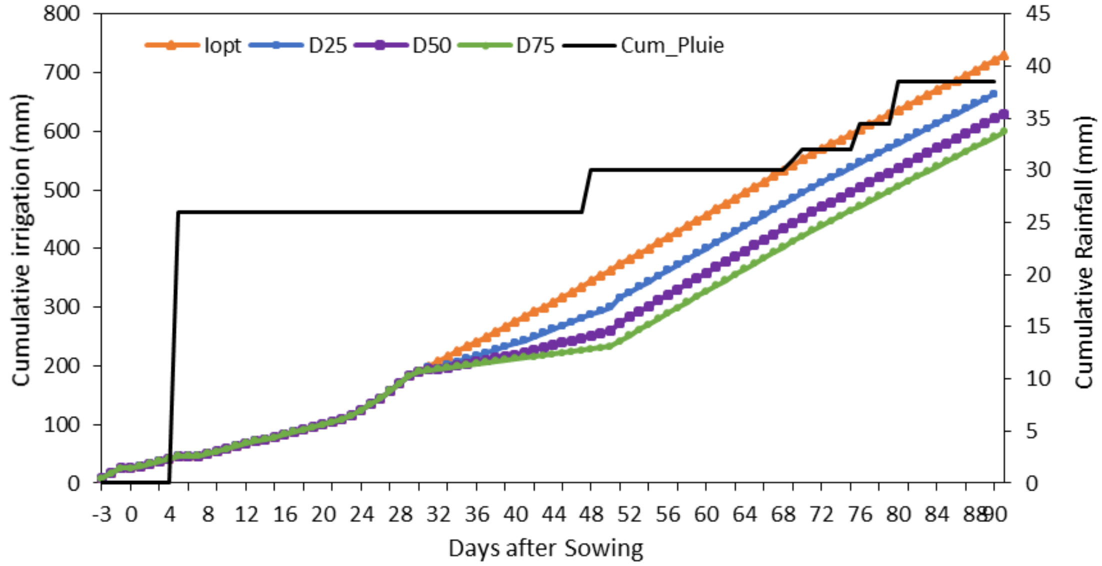


Figure 3. 14: Cumulative irrigation and rainfall recorded during 2019 growing season

3.6.2. Evaluation of Maize growth parameters under deficit irrigation

The rate of appearance of leaves during the development stage of maize was identical for all treatments from zero (0) to 36 DAS, and thereafter from 63 to 69 DAS (**Figure 3.15-A**). During the stage of reduced water supplies, number of leaves significantly reduced for D50 and D75 treatments compared to D0 and D25, where the highest number of leaves was recorded (19). Discrimination of leave number between treatments started from 36 DAS onwards. The highest number of leaves for Do treatments was observed at 51 DAS for D0, 57 DAS for D25, D50, and D75. The number of leaves was lowest for D50 from 39 to 69 DAS.

Leaf area index significantly reduced across treatments due to deficit water from 41 DAS (**Figure 3.15-B**). However there was no significant difference between LAI across treatment from 12 DAS to 39 DAS. It was observed that from 63 DAS, LAI for D25 treatment was slightly higher than that of D0 treatment. LAI in D0 treatments reduced by 24% compared to D25 treatments at 84DAS while the crop height similarly reduced by 30% in D0 treatments compared to D25 treatments

Maize height was affected by deficit irrigation from 39 to 69 DAS. Highest height values were observed in D25 treatment and lowest values were observed in D75 (**Figure 3.15-C**).

Overall temporal biomass increased from 18 DAS to 90DAS for all treatment (**Figure 3.15-D**). Temporal biomass was similar for all treatments from 18 to 36DAS. However, as a result of water stress, biomass significantly reduced for D75 treatment compared to the optimal treatment D0. Between 54 and 63 DAS, there was no significant difference between biomass of D50 and D25 treatment. Reducing 25%, 50% and 75% of crop water need resulted in 23%, 32% and 50% reduction in biomass respectively at 90DAS.

The reduction of irrigation water from 31 DAS to 50DAS induced significant reduction of yield components as shown in **Table 3.5**. Grain yield per cob, number of grain per cob, and thousand grain yield was lowest for D75 treatment, and highest for D0 treatment ($p<0.001$; $p<0.05$; and <0.001 respectively). Thousand (1000) grains weight for D25 and D50 treatments were similar. Similar trend was observed for harvest index, with lowest values given by D75 treatment and highest value given by D0 treatment.

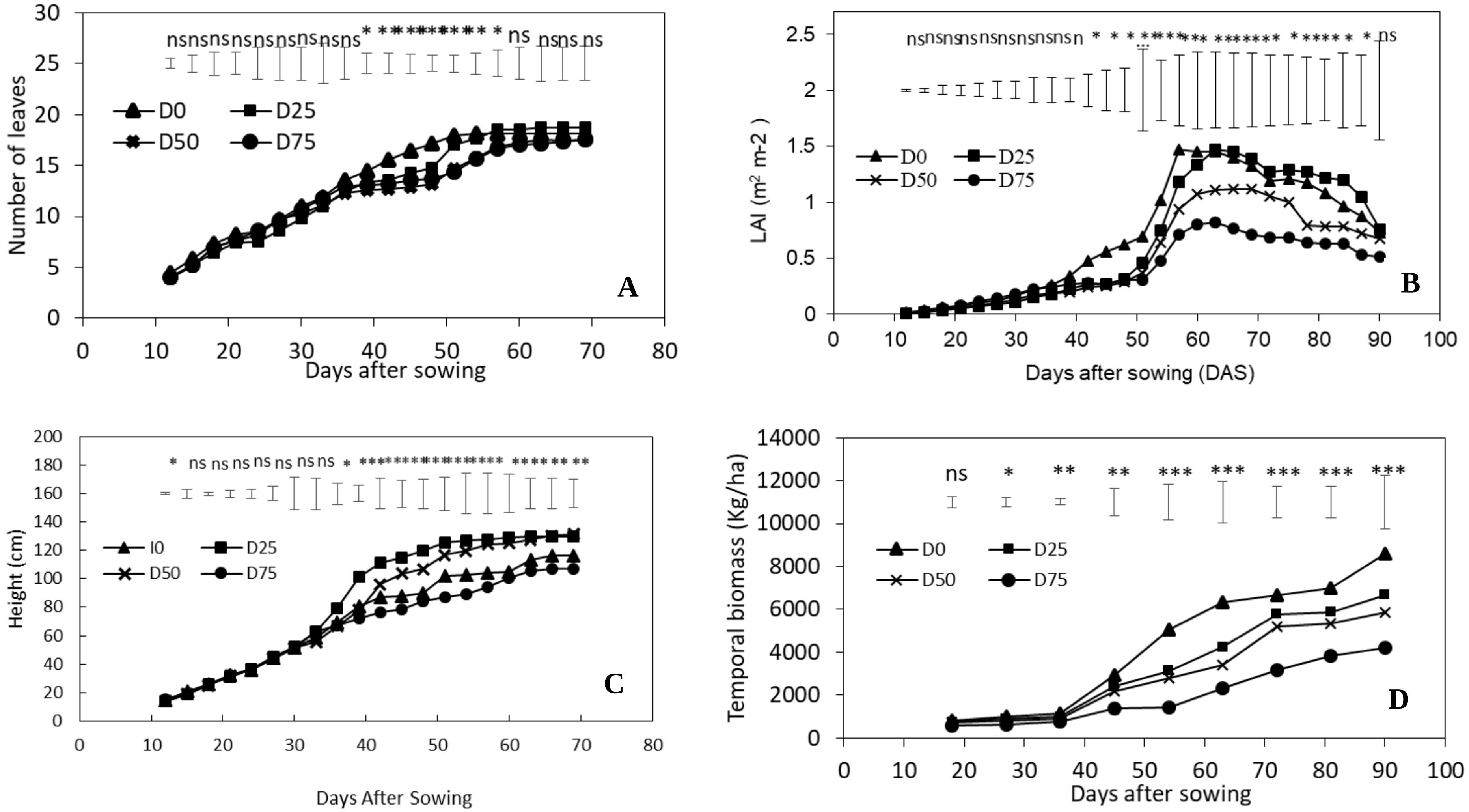


Figure 3. 15: A: number of leaves; B: Leaf Area Index, C: height, and D: temporal biomass of maize during dry season growing (2019) across treatment. Bars represent least square differences across treatments means. '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1: Significance levels of means difference.

Table 3. 5: Yield components of maize during the 2019 offseason cropping season under different deficit irrigations at Parakou in Benin. Anova results are presented in **Appendice 10**

Yield Components	Treatments					
	D0	D25	D50	D75	LSD	p-value
Harvest Index	0.33[a]	0.29[ab]	0.28[b]	0.15[c]	0.044	0.000245 ***
Thousand grain yield (kg)	0.230[a]	0.150[b]	0.130[b]	0.100[c]	0.027	9.51e-05 ***
Number of grain per cob	249[a]	219[ab]	177[bc]	160[c]	50.681	0.0182 *
Grain Weight per Cob (g)	60.83[a]	39.66[b]	28.93[c]	13.44[d]	9.340	9.62e-05 ***
Number of full cobs $plant^{-1}$	1[a]	1[a]	1[a]	1[a]	8.87e-16	0.455[ns]
Number of empty cobs per plants	0[a]	1[b]	1[b]	1[b]	0.789	0.00958 **

'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1: significance levels of means difference; LSD: Least Significant difference of each parameter between treatment

There was a significant treatment effect in maize grain yield and stover yield (p<0.001) and (p<0.01) respectively (**Figures 3.16 A & B**). Water stress level of 25%, 50%, and 75% of induced 25%, 47%, and 82% of yield reduction in D25, D50, and D75 treatments respectively (**Figure 3.16 A**). Similar trend were observed for stover yield as 9%, 31% and 47% of stover reduction were induced as a result of 25%, 50% and 75% of water stress applied respectively (**Figure 3.16 B).** Overall, highest grain yield and stover yield were achieved for the optimal treatment with no water stress. There was no significant difference of stover yield between D0 and D25 in one side, and between D50 and D75 on the other side. Stover yield was similar between D0 and D25 treatments on one side, and between D50 and D75 treatments on the other side.

Maize WUE and IWUE are significantly different among treatments (p<0.001). IWUE is the same for D0 and D25 treatments. IWUE decreased by 28% and 71% in D50 and D75 treatments respectively compared to D0 treatments (**Figure 3.17 A**). WUE decreased by 19% in D25, 24% in D50, and 66% in D75 (**Figure 3.17 B**).

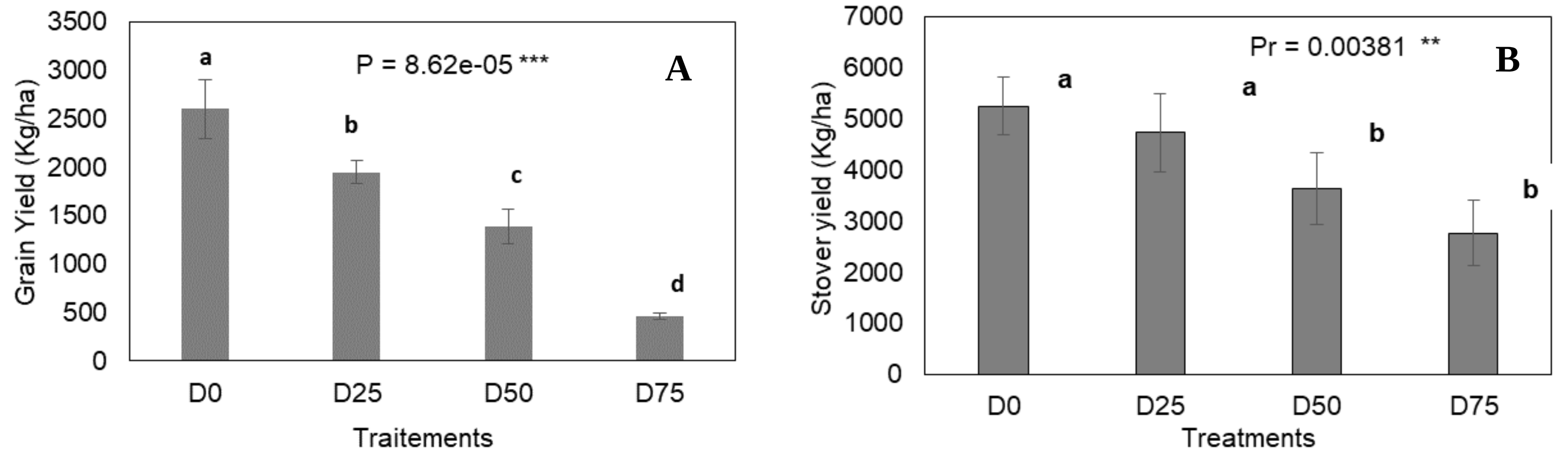


Figure 3. 16: A: Maize grain yield, and B: stover yield in kg ha^{-1} of maize grown under deficit irrigation. Bars represent standard errors. '***' 0.001 '**' 0.01: significance levels of difference in treatment means. Anova results are presented in Appendice 11

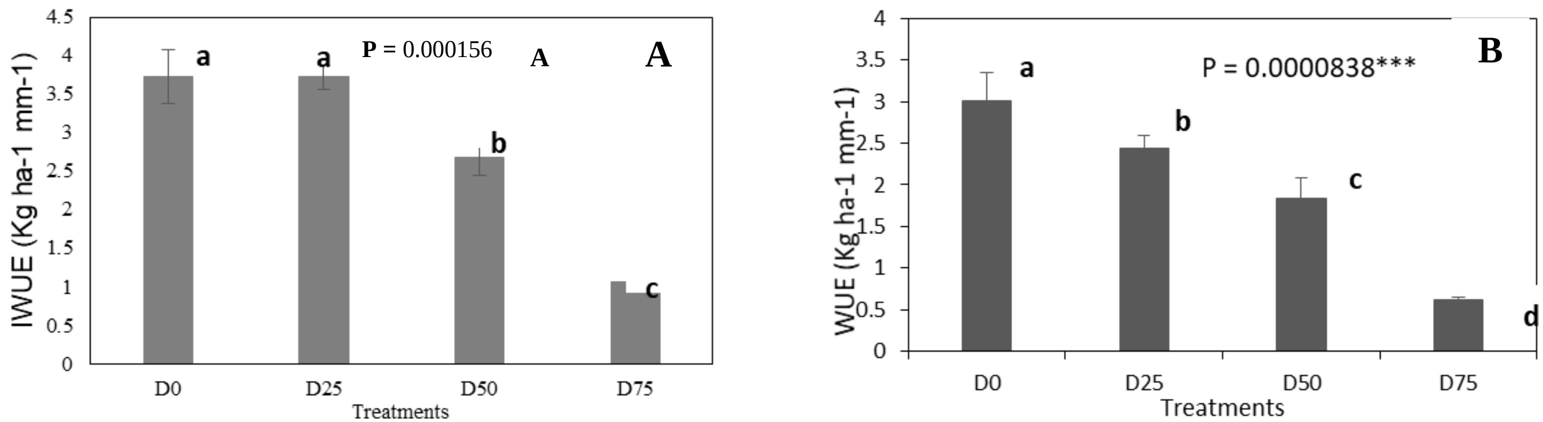


Figure 3. 17: A: Water productivity, and B: water use efficiency of maize grown under deficit irrigation. Bars represent standard errors. '***' 0.001 '**' 0.01: significance levels of difference in treatment means. Anova results are presented in Appendice 12

4.1.Climatic zone of interest of deficit irrigation studies

This review revealed that few studies have been reported from humid zones (**Figure 3.4, and Figure 3.6**). Authors from the studies applied relatively lower water stress levels in arid and semi-arid zones compared to humid zones). The application of lower water stress levels in arid zones can be understood as a precaution taken to avoid total crop failure under the combination of high deficit level and high evaporative demand. Furthermore, the observations confirm that much concern is given to deficit irrigation in arid and semi-arid zone in the view to optimize the use of limited water resources for crop production.

4.2.Maize response to deficit irrigation varies with growth stages

The results of this review show that when water stress is applied at vegetative stage yield loss is low than other stage (**Figure 3.6**). This explains why best deficit irrigation strategies target the most the vegetative stage in existing literature. Many studies identified the reproductive stage, namely the anthesis, and the phase immediately following anthesis as the most sensitive to water deficit (Andrade et al., 2002; Moser et al., 2006; Wang et al., 2017). This study lie in the same conclusions with previous ones in the sense that, under the same water deficit level, yield loss is greater in reproductive stage than in the vegetative stage. Since post-anthesis photosynthesis greatly determines the most carbohydrates in maize grain, any stress during that stage would induce considerable yield loss. Moreover, as a C4 plant, maize suffers more from water stress because of reduced energy captured from sunlight to synthetize carbohydrate during the photosynthesis process. Closed stomata induced by water stress limit the absorption of carbon dioxide, light and water for the synthesis of carbohydrates.

Under the same range of stress set simultaneously at vegetative and reproductive stages, yield loss was expected to be higher than that obtained in vegetative or reproductive stages. Surprisingly, our result show that overall, in that case, yield loss is even lower compared to the loss induced in the reproductive stage. These contrasting results may be explained by a possible accommodation of the crop to the stress from early vegetative growth stage, which may have resulted in yield compensation, under additional stress at reproductive stage. Several studies have indicated that when no stress is given to the crop at vegetative stage, yield loss due to moisture stress during following growth stages (reproductive or maturity) is higher (Comas et al, 2019).

Since yield loss can be substantially reduced in vegetative stage, it is essential to identify specific period at which the crop would be subject to stress with no significant yield loss. Previous studies suggested that a mild to moderate degree of water stress at early vegetative growth stage can maintain or even increase yield (Du et al, 2015). The observations made from our analysis confirm that statement since lowest yield loss were recorded in treatments that underwent water stress in early vegetative stage (e.g. Eck, 1984). Furthermore, exceptional cases were recorded where some yield was gained under stress in vegetative stage. These cases represented 10% of the observations at vegetative stage and gain of grain yield ranged from 0.5 to 5% of optimal yield with no water stress (Ayana, 2011; Eck, 1984).

4.3. Factors explaining variability in maize grain yield and IWUE under deficit irrigation

The results of this study show that both yield loss and IWUE increase as water stress percentage increases. Increase of IWUE irrespective of growth stages indicates that globally, high grain yield can be achieved per unit of irrigation water supplied in treatments under water stress than those under optimal irrigation. Even though water stress is significantly correlated and explains part of yield loss and IWUE proportion in VS and RS, one should not overlook the percentage of the variance that remains unexplained by water stress alone. This implies that other factors than water stress, together with water stress explain better the variability observed, in particular at reproductive stage. Deep insight into the results suggests that maize grain variability can be observed at different levels. In first place, at each growth stage, there is a variability among treatments of same water stress level and from same climatic regions. To illustrate this fact, in humid temperate regions, 50 % of water stress in RS, induced 49% of grain yield loss in one side (Çakir, 2004) whereas 3.20% of yield loss was caused by 50% of stress on another side (Di Paolo and Rinaldi, 2008). In hot semi-arid climate, 28% of stress in VRS, reduced yield up to 21% in P3Kollo cultivar (Pandey et al., 2000), when 28% of stress caused 86% of yield loss in Pioneer 31-R-88 cultivar (Hammad et al., 2012). In the second hand, there is variability among treatments under same water stress level and from different climatic regions. 15% of stress led to 14% of yield loss in Hybrid Kaytar KX-8615Bt cultivar and 25% of yield loss in T.C647 respectively in cold dry temperate and hot dry temperate climate. This illustration suggests that the difference in climatic conditions coupled with the difference in cultivar potential explain the difference in yield loss. Furthermore, the general variability in grain yield under DI reflects a parallel discrepancy of optimal yield among optimal treatments across studies. Lower grain yield in optimal irrigation (OI) of 1792 kg ha^{-1}, was obtained in Niger (Pandey et al., 2000), when higher yield under OI was 20520 Kg ha^{-1} in Turkey (Kuşçu and Demir, 2012). Another way this discrepancy can be noticed is that some treatments under DI at VS or RS in one region resulted in higher yield compared to treatments under OI in other regions. This is highlighted by comparing a grain yield of 18060 kg ha^{-1} for 745 mm and 100 kg ha^{-1} N (Kuşçu and Demir, 2012), and a grain yield of 8205kg ha^{-1} for same water and nitrogen amount (Mansouri-Far et al., 2010). Therefore, despite strong correlation of yield loss with water stress at all growth stages, factors such as climatic conditions on the one side, and cultivar potential on the other side are other sources of variance. As it becomes complex to explain grain yield variability, general conclusions cannot be made concerning the yield reduction percentage to be expected for a given percentage of water stress and even, under a given climate.

4.4. Maize response to supplemental irrigation and irrigation water deficit.

Maize yield in SI 2019 was 32.5% and 19% higher than maize yield in SI 2018 for F3 treatments, and F0 treatment respectively. This implies that even without fertilizer, additional water from supplemental irrigation improved crop growth. Yield increase are higher than the value observed by Gadédjisso-Tossou et al., 2018 who found out that yield increased by 7% under supplemental irrigation of 150mm. Similar increase was made for growth parameters as LAI, and height. The results may be explained by the fact that maize received 168 mm in SI 2019, more than what it received in SI 2018. The intra-annual and the inter-annual variability of rainfall was reduced when supplemental irrigation of 40 to 71 mm was introduced.

Deficit irrigation increased LAI in D25 treatments compared to D0 treatments from 63DAS to harvest (**Figure 3.15**). Similar increase of LAI in stressed treatments has been reported in Comas et al, 2019. Yield was reduced in the stress treatments compared to optimal treatment (**Figure 3.16**). Yield reduction observed in this study is within the range of the values reported in previous studies in Niger (Pandey et al, 2000), and in Turkey (Kusçu and Demir, 2012). These authors reported a yield loss in the range of 21-28%, and of 49% under a rate of 28%, and 58% of respective water stress applied. The water stress levels applied significantly decreased grain yield among treatments, but resulted in similar final biomass between D0 and D25 treatments, and D50 and D75 treatments respectively. Yield reduction from this study is explained by the reduction in the number of grain per cob, and the reduction in the 1000 grain dry weight as reported by other researchers (Payero et al, 2009; Aguilar et al, 2007). From our results, the number of grain per cob decreased by 12%, 29% and 36% respectively in D25, D50 and D75 treatments compared to the optimal treatments (Table 3.2). However 1000-grain weight decreased by 35%, 42% and 57% respectively in D25, D50, and D75 treatments. Earlier studies that investigated the physiological, biochemical and developmental processes that underpin yield formation under water stress have reported a closure of plants stomata which limits CO_2 uptake and carbon gain for photosynthesis. In the say way, the closure of stomata would in turn reduce water loss, thereby leading to a possible increase of WUE (Du et al, 2015).

The results on water production and crop water use efficiency revealed that irrigation water can be reduced by 25% (56.72 mm) without impeding production per unit water input (**Figure 3.17**). The grain yield in D50 treatments would have been obtained by saving 6% of the water (31.43mm) applied. WUE is highest in D0 treatments and lowest in D75 treatments that received higher stress levels. WUE reduced by 19%, 24%, and 66% respectively in D25, D50, and D75 treatments compared to D0 treatments.

There was a significant difference in IWUE and WUE among treatments with the highest and lowest IWUE and WUE valued observed in D0 and D75 treatments respectively (**Figure 3.17 B**). However IWUE values were not different between D0 and D25 treatments. This implies that water stress levels D25 is closer to the right irrigation deficit to apply for increased water productivity. IWUE was 28% lower in D50 compared to both D0 and D25 treatments, and was 71% and 60% lower in D75 compared to D0 and D25 treatments respectively. This reduction is far above the reduction percentage of IWUE observed in previous studies which ranged from 1% to 14% under a range of 4 to 17% of stress (Pandey et al, 2000; Mansouri-Far et al, 2014; Kusçu and Demir, 2012). Yield decreases obtained from our results were larger than the range reported by previous studies (Benett et al, 1989), who reported a reduction of yield loss from 51 to 75%.

4.5. Implications and opportunities

It is widely recognized that agriculture is by far the most important driver in the world water use with more than two thirds of the total fresh water resources of the planet consumed in an inefficient manner (Alemu et al., 2017; Viala, 2008). With growth stage based deficit irrigation (DI), there is a potential opportunity to save the amount of water in irrigation (Du et al., 2015; Raza et al., 2012) and hence increase irrigation water use efficiency which is the main goal of DI (Chai et al., 2016). More, probably, the technique offers also an opportunity to increase grain yield. When the increase of water use efficiency is observed generally, the increase of grain yield under this technique is still elusive. Previous reviews of DI had either been explanative, focusing on the mechanisms (physiological and biochemical) with which plants respond to DI (Chai et al., 2016), or comparing many types of crops response under different approaches of DI during plant growing cycle (Adu et al., 2018; Daryanto et al., 2016). The present analysis which focuses on maize response to DI, is in agreement with previous reviews on the fact that yield penalties caused by DI based on growth stage is compensated for with some irrigation water productivity gains. But, the extent to which the deficit can be limited at each growth stage to reduce yield loss and increase IWUE remains explorative.

Although crop yields are ultimate target for farmers in any irrigation strategy, this goal can be compromised by saving water in arid environment where water has an economic value for crop production (Exposito and Berbel, 2016). Thus there is the need to be aware of the factors that could potentially confound the effectiveness of water saving strategies. The results of our analysis showed that maize response to DI vary not only with growth stage but with a diversity of factors inherent to production systems. The complexity of production systems poses therefore a challenge to understand crop response to DI.

Among the factors, climate has a very significant effect on yield under DI. Recent studies proved that temperature and solar radiation are the main climatic parameters explaining maize yield and yield variability under water stress (Carter et al., 2016; Srivastava et al., 2017). Because high temperatures are often recorded in drought periods, it remains unclear whether high temperature impacts yield, independent of moisture stress, at specific growth stages. Despite of the undeniable roles of temperature and solar radiation in the process of crop growth, their significant effect on yield at each separate growth stage need to be investigated.

This review also contributes to the recognition that yield loss induced by water stress during reproductive stage is higher than yield loss in vegetative (Comas et al., 2019; Du et al., 2015; Fereres and Soriano, 2006). One of the key conclusion is that, under the same severity of deficit, yield loss at vegetative stage is less important. The fact that some yield can be gained under deficit water at the vegetative stage cannot, however be generalized, even though some case studies have been recorded which represent 10% of the total VS observations. However this provides an opportunity to investigate on the level of stress to be applied in the early vegetative stages, so as to provide some meaningful range to farm managers. Mainly for maize crop, focus should rather be on variability of water productivity and efficiency under deficit irrigation. Because yield loss is inevitable irrespective of growth stages, there is a need to optimize yield loss in conjunction with water productivity gain under range of factors that are in reality dependent on region (Mueller et al., 2012).

Site specific recommendations on level of water stress at each crop growth stage, from seedling to maturity, through use of decision support tools (DST) (MacCarthy et al., 2018) could be of great deal to limit yield loss and increase water productivity under a range of factors. This would require the development of models that will be able to represent the real situations and make recommendations. This would be highly beneficial to farmers in arid areas where water use has an economic value, to help them increase their monetary return in water. So far, the uses of existing models have been limited to irrigation scheduling (defining the timing for deficit irrigation), and are rarely oriented towards site-specific recommendation for peculiar range of factors. The intent was mainly to calibrate and validate models (Andarzian et al., 2011; Farahani et al., 2009; Heng et al., 2009; Hsiao et al., 2009; Khaledian et al., 2009; Ran H. et al., 2018); or to simulate crop yield under future climate (Folberth, 2013; Katerji et al., 2013; Ma et al., 2017; Tsakmakis et al., 2019). New operating fields of DST need to be geared toward optimizing crop yield under DI.

Deficit irrigation has proved to be beneficial in many studies, but the benefits are perceived based on the starting goal before irrigation. The results of this study, conducted under sub-humid climate in Benin indicated that stover yield at harvest was similar between D0 and D25 treatments on one side and between D50 and D75 on the other side. At the same time, similar results were obtained for IWUE between the two treatments. These results depict a similar water resources allocation in the pair treatments similar to each other, and proves its efficiency in reducing IWUE. But the results show that IWUE from stover yield will be higher than IWUE from grain yield. This would be more interesting if the prior goal of the irrigation was to produce maize forage, for animal feeding for instance. Hence, its importance to define the goals of deficit irrigation before implementing it.

Deficit irrigation (DI) is an irrigation strategy to increase WUE in water limiting environment, hence its prior objective is not to increase crop yield. The importance of DI has also been debated in environments where water used for crop production has a monetary price, and where the objective is to reduce irrigation cost due to water pricing. Farmers in West Africa are not always concerned by increased grain yield, but by a sustained yield over long period of time, which is often jeopardized by climate variability. In such context, using deficit irrigation in sub-humid climate under the tropics, can be perceived not as a means to increase yield, but as a way to anticipate (i) unfavorable growing seasons with frequent drought spells and untiming effective onset of raining season, thereby maintaining crop yield and (ii) the competitive use of fresh water resources among economic sectors in that part of the world.

To improve DI schedules, the growth stages and the DI amount should be determined. Identifying these key parameters in DI scheduling through experiments would be quite time consuming, expensive, and laborious. Crop models can play an important role in identifying efficient DI schedules that would limit yield loss. Moreover, when coupled with climatic scenarios, they can simulate for long term efficient DI. Thus further study should consider the role crop model can play to maintain crop productivity under DI in WA.

4.6.Limits of the study

Water stress affects crop through three main processes: crop photosynthesis, crop phenology, and leaf expansion. Data from crop phenology would have provided detailed information on the duration of each growth stage under different levels of stress. Finally, irrigation of cereal in general is yet not common in WA, and its implementation needs to be economically profitable for farmers. Therefore, further studies are needed to investigate the economic sustainability of the strategy in WA.

CHAPTER V: CONCLUSIONS AND OUTLOOK

In SSA, maize production systems are limited by unstable rainfall season, which in some parts manifest by frequent drought spells, leading to crop failure. To face this situation, new water management strategies can help to maintain and stabilize crop yield. This study has tested supplemental irrigation (SI) and deficit irrigation (DI) as such water management strategies to improve on maize production in a sub-humid climate of West Africa. Through a quantitative review on maize response to irrigation water stress, the results revealed that maize crop is more sensitive to DI at its reproductive stage (RS) than any other stage, with the highest yield loss compared to vegetative stage. Under low stress (20%) in VS, maize loss varied from 0.5% to 17.45% of its optimal yield. In RS, yield loss can reach 46%. 0.70 to 30% yield loss occurred below 20%. Lower yield loss is achieved at all stages, for lower water stress. Generally, yield loss was reduced when the stress occurred in early vegetative stage or in late reproductive stage (dough R4, dent R5, and physiological maturity R6), providing that the crop suffered no stress at establishment and beginning of reproductive stage. Maize yield variability under water stress was not explained only by water stress, but also by other external factors such as climate (temperature, solar radiation), cultivar cycle and nitrogen rates. However the significant effect of these factors combined together varies from one stage to the other. Water stress and climate greatly explained yield variability in vegetative and reproductive stage. When stress occurs at bot vegetative and reproductive stages, all the factors were explanative. With regards to IWUE, much irrigation water can be saved in maize stressed both at vegetative and reproductive stages. These results should be taken with precaution, however, because they do not reflect the difference in the frequency of irrigation at either stage. In addition, the variable IWUE does not reflect the production of biomass or yield per unit water used by the crop (ET) or per unit of water transpired, nor does it specify that water lost by irrigation is reused by other uses. Given the heterogeneous characteristics of experimental sites, there is need for site specific recommendations on level of water stress at each crop growth stage, through use of crop models to limit yield loss.

The experiments conducted focused on maize growth and yield. Supplemental irrigation improved maize production for all parameters compared to deficit irrigation. Irrigation water stress induced a decrease in number of leaves, LAI, height and temporal biomass starting from different dates, in D50 and D75 treatments compared to D25 and D0 treatments. Number of total leaves, LAI and height in D25 increased compared to D0 treatments. This explains the similar stover yield at harvest in the two treatments. Lower biomass reduction in D25 treatments supports the use of DI strategy for stover production used to feed animal. Therefore the results of this study suggest that the objective of using deficit irrigation for maize production should be clearly stated, as grain yield loss is obvious. As yield loss increases with levels of water stress, it is important to determine the optimum level of deficit irrigation level for which yield loss would be reduced. Since farmers in West Africa context are more concerned about a sustained yield over a long period of time, that optimum deficit level should be determined to make appropriate recommendations. Technically, as the proposed strategies are not yet implemented and practiced by farmers in WA, especially in Benin, many questions can be raise as for the acceptability of the strategies and their economic viability, provided that they can be implemented.

References

1. Adger WN, Agrawala S, Mirza MMQ. Assessment of adaptation practices, management options, constraints and capacity. Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, 2007.
2. Adu MO, Yawson DO, Armah FA, Asare PA, Frimpong KA. Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. *Agricultural Water Management*, 2018; 197, 79–90. **https://doi.org/10.1016/j.agwat.2017.11.019**
3. Agbossou EK, Toukon C, Akponikpè PBI, Afouda A. Climate Variability and Implications for Maize Production in Benin: A Stochastic Rainfall Analysis. *African Crop Science Journal*, 2012; 20 (2): 493 – 503.
4. Aguilar M, Borja FS, Espinosa M. Agronomic response of maize to limited levels of water under furrow irrigation in southern Spain. *Spanish Journal of Agricultural Research*, 2007; 5(4), 587-592**.**
5. Ahokpossi Y. Analysis of the rainfall variability and change in the Republic of Benin (West Africa). *Hydrological Sciences Journal*, 2018; 63, Issue 15-16. https://doi.org/10.1080/02626667.2018.1554286
6. Alemu GT, Berhane Z, Gashaw A. IRRIGATION WATER USE EFFICIENCY: REVIEW. Journal of Radix International Educational and Research Consortium, 2017; 6.
7. Ali S, Hafeez A, Ma X, Tung SA, Liu A, Shah AN, Chattha MS, Zhang Z, Yang G. Potassium relative ratio to nitrogen considerably favors carbon metabolism in late-planted cotton at high planting density. *Field Crops Research* , 2018; 223, 48–56. **https://doi.org/10.1016/j.fcr.2018.04.005**
8. Ali AB, Hong L, Elshaikh N, Yan Haofang Y. The Role of Supplemental Irrigation to Crop Water Use under Rainwater Harvesting. *Biosci. J.*, 2017; 33 (4) : 944-955.
9. Alissou E, Huat J, Assogba Komlan F, Amadji G. Diversité des modes de conduite des cultures de contre saison dans les bas-fonds rizicoles du Mono et du Couffo au Sud-Bénin. Poster presenté à Atelier final projet RAP, AfricaRice, Cotonou, Bénin, 2010.

10. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration – guidelines for computing crop water requirements-FAO Irrigation and Drainage Paper 56. FAO, 1998. ISBN 92-5-104219-5.

11. Amali AA, Bala MS, Adeniji FA. Dying Lake Chad: Adaptive Strategies to Climate Change and Water Scarcity of the Lake Chad Basin, 2016; 12p.

12. Amegnaglo CJ. Determinants of maize farmers' performance in Benin, West Africa. *Kasetsart Journal of Social Sciences*, 2018; 2 (11) : 1-7, 2097-2123 https://doi.org/10.1016/j.kjss.2018.02.011

13. Andarzian B, Bannayan M, Steduto P, Mazraeh H, Barati ME, Barati MA, Rahnama A. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agricultural Water Management* 2011; 100, 1–8. **https://doi.org/10.1016/j.agwat.2011.08.023**

14. Andrade FH, Echarte L, Rizzalli R, Della Maggiora A, Casanovas M. Kernel Number Prediction in Maize under Nitrogen or Water Stress. *Crop Sci.* 2002; 42:1173–1179

15. Aslam M, Zamir MSI, Afzal I, Yaseen M, Mubeen M, Shoaib A. Drought Stress, its Effect on Maize Production And Development Of Drought Tolerance Through Potassium Application. *Cercetări Agronomice în Moldova* 2013; XLVI, 99–114.

16. Ayana M. Deficit irrigation practices as alternative means of improving water use efficiencies in irrigated agriculture: Case study of maize crop at Arba Minch, Ethiopia. *African Journal of Agricultural Research*, 2011; 6, 10. https://doi.org/10.5897/AJAR09.118

17. Azontonde HA. Propriétés physiques et hydrauliques des sols au Bénin. Soil Water Balance in the Sudano Sahelian Zone (Proceedings of the Niamey Workshop, February 1991). *IAHS*, 1991; Publ. no. 199, 249-258.

18. Baco MN, Abdoulaye T, Sanogo D, Langyintuo A. Caractérisation des ménages producteurs de maïs en zone de savane sèche au Bénin. Rapport pays—Enquête-ménage – Benin. IITA Ibadan, Nigeria, 2010; 38 pp.

19. Bennett JM, Mutti LSM, Rao PSC, Jones JW. Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. *Field Crops Research*, 1989; 19, 297–311. **https://doi.org/10.1016/0378-4290(89)90100-7**

20. Blein R, Bio Goura S, Dupaigre BF, Yérima B. Les potentialités agricoles de l'Afrique de l'Ouest (CEDEAO). 2008; 116p.

21. Çakir R. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research*, 2004; 89, 1–16. **https://doi.org/10.1016/j.fcr.2004.01.005**

22. Carter EK, Melkonian J, Riha SJ, Shaw SB. Separating heat stress from moisture stress: analyzing yield response to high temperature in irrigated maize. *Environmental Research Letters*, 2016; 11, 094012. https://doi.org/10.1088/1748-9326/11/9/094012

23. Cassardo C, Jones JAA. Managing Water in a Changing World. *Water*, 2011; 3, 618–628. https://doi.org/10.3390/w3020618

24. Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y, Siddique KHM. Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for Sustainable Development*, 2016; 36. https://doi.org/10.1007/s13593-015-0338-6.

25. Chauvin ND, Mulangu F, Porto G. Food Production and Consumption Trends in Sub-Saharan Africa: Prospects for the Transformation of the Agricultural Sector. Working Paper, 2012-011. 76p.

26. Comas LH, Trout TJ, DeJonge KC, Zhang H, Gleason SM. Water productivity under strategic growth stage-based deficit irrigation in maize. *Agricultural Water Management*, 2019; 212, 433–440. https://doi.org/10.1016/j.agwat.2018.07.015

27. Cui N, Du T, Li F, Tong L, Kang S, Wang M, Liu X, Li Z. Response of vegetative growth and fruit development to regulated deficit irrigation at different growth stages of pear-jujube tree. *Agric Water Manag*, 2009; 96:1237–1246. https://doi.org/10.1016/j.agwat.2009.03. 015

28. Daryanto S, Wang L, Jacinthe PA. Global Synthesis of Drought Effects on Maize and Wheat Production. *PLOS ONE*, 2016; 11, e0156362. https://doi.org/10.1371/journal.pone.0156362

29. Di Paolo E, Rinaldi M. Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. *Field Crops Research* 2008; 105, 202–210. https://doi.org/10.1016/j.fcr.2007.10.004

30. Diwediga B, Hounkpe K, Wala K, Batawila K, Tatoni T, Akpagana K. *African Crop Science Journal*, 2012; 20 (s2) : 613-624.

31. Djossou J, Akpo AB, Afféwé JD, Donnou VHE, Liousse C, Jean-François Léon JF, Nonfodji FG, Awanou CN. Dynamics of the Inter Tropical Front and Rainy Season Onset in Benin. *Current Journal of Applied Science and Technology*, 2017; 24(2): 1-15.

32. Domínguez A, de Juan JA, Tarjuelo JM, Martínez RS, Martínez-Romero A. Determination of optimal regulated deficit irrigation strategies for maize in a semi-arid environment. *Agricultural Water Management*, 2012; 110, 67–77. https://doi.org/10.1016/j.agwat.2012.04.002

33. Doto VC, Yacouba H, Niang D, Lahmar R, Agbossou EK. Mitigation effect of dry spells in Sahelian rainfed agriculture: Case study of supplemental irrigation in Burkina Faso. *Academic Journal*, 2015; 10 (16) : 1863-1873, http://dx.doi.org/10.5897/AJAR2015.9639

34. Du T, Kang S, Zhang J, Davies WJ. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. *J Exp Bot*, 2015; 66, 2253–2269. https://doi.org/10.1093/jxb/erv034

35. Eck HV. Irrigated Corn Yield Response to Nitrogen and Water. *Agronomy Journal*, 1984; 76, 421–428. https://doi.org/10.2134/agronj1984.00021962007600030014x

36. Ertek A, Kara B. Yield and quality of sweet corn under deficit irrigation. *Agricultural Water Management*, 2013; 129: 138– 144. http://dx.doi.org/10.1016/j.agwat.2013.07.012

37. Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use: INCREASING WATER USE EFFICIENCIES. *Water Resources Research*, 2008; 44. https://doi.org/10.1029/2007WR006200

38. Exposito A, Berbel J. Why Is Water Pricing Ineffective for Deficit Irrigation Schemes? A Case Study in Southern Spain. *Water Resources Management*, 2016; **https://doi.org/10.1007/s11269-016-1563-8**

39. Fabeiro C, Martin de Santa Olalla F, de Juan JA. Yield and Size of deficit irrigation potatoes. *Agricultural Water Management*, 2003; 48 : 255-266.

40. FAO. L'état de l'insécurité alimentaire dans le monde. Éradiquer la faim dans le monde -bilan 10 ans après le Sommet mondial de l'alimentation, 2006; 44p.

41. Farahani HJ, Izzi G, Oweis TY. Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton. *Agronomy Journal*, 2009; 101, 469. https://doi.org/10.2134/agronj2008.0182s

42. Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 2006; 58, 147–159. https://doi.org/10.1093/jxb/erl165

43. FAOSTAT, 2017. http://www.fao.org/faostat/en/#home

44. Farré I, Faci JM. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agricultural Water Management*, 2009: 96: 383-394. http://.doi.org/10.1016/j.agwat.2008.07.002

45. Folberth,C. Modeling crop yield and water use in the context of global change with a focus on maize in sub-Saharan Africa. ETH Zurich, 2013. https://doi.org/10.3929/ethz-a-010113683

46. FAO (Food and Agriculture Organization). Coping with water scarcity in agriculture: a global framework for action in a changing climate, 2016; 12p.

47. Gadédjisso-Tossou A, Avellán T, Schütze N. Potential of Deficit and Supplemental Irrigation under Climate Variability in Northern Togo, West Africa. *Water*, 2018; 10, 1803, 23p. https://doi.org/10.3390/w10121803

48. García DelMoral LF, Rharrabti Y, Villegas D, Royo C. Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: an ontogenic approach. *Agron J*, 2003; 95: 266–274. https://doi.org/10.2134/agronj2003.0266

49. Gashu D, Demment MW, Stoecker BJ. Challenges and pportunities to the African agriculture and food systems. *Afr. J. Food Agric. Nutr. Dev*, 2019; 19 (1):14190-14217. https://doi.org/ 10.18697/ajfand.84.BLFB2000

50. Geerts S, Raes D, Garcia M, Vacher J, Mamani R, Mendoza J, Huanca R, Morales B, Miranda R, Cusicanqui J, Taboada C. Introducing deficit irrigation to stablize yields of quinoa (Chenopodium quinoa Willd.). *Eur. J. Agron*, 2008a; 28, 427–436.

51. Geerts S, Raes D, Garcia M, Condori O, Mamani J, Miranda R, Cusicanqui J, Taboada C, Vacher J. Could deficit irrigation be a sustainable practice for quinoa (Chenopodium quinoa Willd.) in the Southern Bolivian Altiplano? *Agric. Water Manag* 2008b. 95, 909–917.

52. Gheysari M, Sadeghi S.-H, Loescher HW, Amiri S, Zareian MJ, Majidi MM, Asgarinia P, Payero JO. Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. *Agricultural Water Management*, 2017; 182, 126–138. https://doi.org/10.1016/j.agwat.2016.12.014

53. Gouranga K, Harsh NV. Phenology based irrigation scheduling and determination of crop coefficient of winter maize in rice fallow of eastern India. *Agricultural Water Management*, 2005; 75: 169–183. http://dx.doi.org/10.1016/j.agwat.2005.01.002

54. Gruber I., Kloos J., Schopp M., 2009. Seasonal water demand in Benin's agriculture. *Journal of Environmental Management*, 90 (1): 196-205. https://doi.org/10.1016/j.jenvman.2007.08.011

55. Haghverdi A, Leib B, Washington-Allen R, Wright WC, Ghodsi S, Grant T, Zheng M, Vanchiason P. Studying Crop Yield Response to Supplemental Irrigation and the Spatial Heterogeneity of Soil Physical Attributes in a Humid Region. *Agriculture*, 2019; 9 (43), https://doi.org /10.3390/agriculture9020043

56. Hammad HM, Ahmad A, Abbas F, Farhad W. Optimizing water and nitrogen use for maize production under semiarid conditions. *Turk J Agric For*, 2012; 36, 519–532. https://doi.org/10.3906/tar-1111-24

57. Hanjra MA, Qureshi ME. Global water crisis and future food security in an era of climate change. *Food Policy*, 2010; 35, 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

58. Heng, LK, Hsiao T, Evett S, Howell T, Steduto P. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agronomy Journal*, 2009; 101, 488–497. https://doi.org/10.2134/agronj2008.0029xs

59. Hsiao TC, Heng L, Steduto P, Rojas-Lara B, Raes D, Fereres E. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agronomy Journal*, 2009; 101, 448. https://doi.org/10.2134/agronj2008.0218s

60. Hu T, Yuan L, Wang J, Kang S, Li F. Antioxidation responses of maize roots and leaves to partial root-zone irrigation. *Agricultural Water Management*, 2010; 98, 164–171. https://doi.org/10.1016/j.agwat.2010.06.019

61. Huang M, Zhong L, Gallichand J. Irrigation treatments for corn with limited water supply in the Loess Plateau, China. *Canadian Biosystems Engineering*, 2002; 44 (1): 29-34**.**

62. Jones PG, Thornton PK. The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, 2003; 13, 51–59. http://.doi.org/10.1016/S0959-3780(02)00090-0

63. Kadjo D, Ricker-Gilbert J, Alexander C, Tahirou A. Effects of Storage Losses and Grain Management Practices on Storage: Evidence from Maize Production in Benin. Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, 2013; 37p.

64. Kang S, Zhang L, Xiaotao H, Li Z, Jerie P. An improved water use efficiency for hot pepper grown under controlled alternate drip irrigation on partial roots. *Sci. Hort.*, 2001; 89, 257–267.

65. Katerji N, Campi P, Mastrorilli M. Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region. *Agricultural Water Management*, 2013; 130, 14–26.

66. Khaledian MR, Mailhol JC, Ruelle P, Rosique JL. Adapting PILOTE model for water and yield management under direct seeding system: The case of corn and durum wheat in a Mediterranean context. *Agricultural Water Management*, 2009; 96, 757–770. https://doi.org/10.1016/j.agwat.2008.10.011

67. Kirda C, Kanber R, Tulucu K. Yield response of cotton, maize, soybean, sugar beet, sunflower and wheat to deficit irrigation. In: Kirda C, Moutonnet P, Hera C, Nielsen DR, eds. *Crop yield response to deficit irrigation*, Dordrecht, The Netherlands, Kluwer Academic Publishers, 1999.

68. Kirda C, Topcu S, Kaman H, Ulger AC, Yazici A, Cetin M, Derici MR. Grain yield response and N-fertiliser recovery of maize under deficit irrigation. *Field Crops Research*, 2005; 93, 132–141. https://doi.org/10.1016/j.fcr.2004.09.015

69. Kusçu H, Demir AO. Responses of Maize to Full and Limited Irrigation at Different Plant Growth Stages. *Journal of Agricultural Faculty of Uludag University*, 2012; 26 (2): 15-27.

70. Li F, Liang J, Kang S, Zhang J. Benefits of alternate partial root-zone irrigation on growth, water and nitrogen use efficiencies modified by fertilization

and soil water status in maize. *Plant and Soil*, 2007; 295, 279–291. https://doi.org/10.1007/s11104-007-9283-8

71. Lobell DB, Banziger M, Magorokosho C, Vivek B. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, 2011; 1(1), 42-45.

72. Ma L, Ahuja LR, Islam A, Trout TJ, Saseendran SA, Malone RW. Modeling yield and biomass responses of maize cultivars to climate change under full and deficit irrigation. *Agricultural Water Management*, 2017; 180, 88–98. https://doi.org/10.1016/j.agwat.2016.11.007

73. MacCarthy DS, Kihara J, Masikati P, Adiku SGK. Decision support tools for site-specific fertilizer recommendations and agricultural planning in selected countries in sub-Sahara Africa. *Nutrient Cycling in Agroecosystems*, 2018; 110, 343–359. https://doi.org/10.1007/s10705-017-9877-3

74. Magrin G. The disappearance of Lake Chad: history of a myth. *Journal of Political Ecology*, 2016; 23, 204. https://doi.org/10.2458/v23i1.20191

75. Mansouri-Far C, Modarres Sanavy SAM, Saberali SF. Maize yield response to deficit irrigation during low-sensitive growth stages and nitrogen rate under semi-arid climatic conditions. *Agricultural Water Management*, 2010; 97, 12–22. https://doi.org/10.1016/j.agwat.2009.08.003

76. MEPN. Ministère de l'Agriculture, de l'Elevage et de la Pêche, 2008. Carte du Bénin présentant les zones agroécologiques. 2008.

77. Meng W, Yu Z, Zhang Y, Shi Y, Wang D. Effects of supplemental irrigation on water consumption characteristics and grain yield in different wheat cultivars. *Chilean Journal of Agricultural Research*, 2014; 75(2): 216-223. https://doi.org/10.4067/S0718-58392015000200011

78. Mishra M, Kumar U, Prakash V. Influence of Salicylic Acid Pre-Treatment On Water Stress And Its Relationship With Antioxidant Status In Glycine Max 18. 2013.

79. Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J. Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, 2010; 97, 528–535. https://doi.org/10.1016/j.agwat.2009.03.023

80. Molden DJ, Murray-Rust H, Sakthivadivel R, Makin IW. A water-productivity framework for understanding and action. 2003.

81. Mollier A, Pellerin S. Maize root system growth and development as influenced by phosphorus deficiency. *Journal of Experimental Botany*, 1999; 20, 487–497.

82. Moser SB, Feil BA, Jampatong S, Stamp P. Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. *Agricultural Water Management*, 2006; 81: 41–58

83. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. Closing yield gaps through nutrient and water management. *Nature*, 2012; 490, 254–257. **https://doi.org/10.1038/nature11420**

84. Ndehedehe CE. The water resources of tropical West Africa: problems, progress, and prospects. *Acta Geophysica*, 2019; 67:621–649, https://doi.org/10.1007/s11600-019-00260-y

85. NeSmith DS, Ritchie JT. Effects of soil water-deficits during tassel emergence on development and yield component of maize (*Zea mays*). *Field Crops Research*, 1992; 28 : 251-256**.**

86. ONASA (Officie National d'Appui à la sécurité Alimentaire). Evaluation de la production vivrière 2015 et des perspectives alimentaires pour 2016 au Bénin. Rapport Général, 2016, 1, 221 pp.

87. Ohyama T. Nitrogen as a major essential element of plants, 2010.

88. Osborne SL, Schepers JS, Francis DD, Schlemmer MR. Use of Spectral Radiance to Estimate In-Season Biomass and Grain Yield in Nitrogen- and Water-Stressed Corn. *Crop Sci*., 2002; 42:165–171.

89. Oweis T, Hachum A. Water Harvesting and Supplemental Irrigation for Improved Water Productivity of Dry Farming Systems in West Asia and North Africa. Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004, Brisbane, Australia. Published on CDROM. www.cropscience.org.au

90. Pandey RK, Maranville JW, Chetima MM. Deficit irrigation and nitrogen effects on maize in a Sahelian environment II. Shoot growth, nitrogen uptake and water extraction. *Agricultural Water Management, 2000;* 13.

91. Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. *Agricultural Water Management*, 2009; 96: 1387–1397. http://dx.doi.org/10.1016/j.agwat.2009.03.022

92. Pérez-Pastor A, Ruiz-Sánchez MC, Domingo R. Effects of timing and intensity of deficit irrigation on vegetative and fruit growth of apricot trees. *Agricultural Water Management*, 2014; 134, 110–118. https://doi.org/10.1016/j.agwat.2013.12.007

93. Plessis AD. Freshwater Challenges of South Africa and its Upper Vaal River: Current State and Outlook, *Springer Water*, 2017. Springer International Publishing.

94. Prajapati K, Modi HA. The Importance of Potassium in Plant Growth – A Review. *Indian Journal of Plant Sciences*, 2012; 02–03, 177–186.

95. Pulido-Velazquez M, Peña-Haro S, García-Prats A, Mocholi-Almudever AF, Henriquez-Dole L, Macian-Sorribes H, Lopez-Nicolas A. Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the Mancha Oriental system (Spain). *Hydrology and Earth System Sciences*, 2015; 19, 1677–1693. https://doi.org/10.5194/hess-19-1677-2015

96. Ran H, Kang S, Li F, Du T, Tong L, Li S, Ding R, Zhang X. Parameterization of the AquaCrop model for full and deficit irrigated maize for seed production in arid Northwest China. *Agricultural Water Management*, 2018; 203, 438–450.

97. Ray DK, Mueller ND, West PC, Foley JA. Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PLoS ONE*, 2013; 8, e66428. https://doi.org/10.1371/journal.pone.0066428

98. Raza A, Friedel JK, Bodner G. Improving Water Use Efficiency for Sustainable Agriculture, in: Lichtfouse, E. (Ed.), Agroecology and Strategies for Climate Change, *Sustainable Agriculture Reviews*, 2012. Springer Netherlands, Dordrecht, pp. 167–211. https://doi.org/10.1007/978-94-007-1905-7_8

99. Romero P, Dodd IC, Martinez-Cutillas A. Contrasting physiological effects of partial root zone drying in field-grown grapevine (*Vitis vinifera L. cv. Monastrell*) according to total soil water availability. *J Exp Bot*, 2012; 63, 4071–4083. https://doi.org/10.1093/jxb/ers088

100. Rosegrant MW, Ringler C, Zhu T. Water for Agriculture: Maintaining Food Security under Growing Scarcity. *Annual Review of Environment and Resources*, 2009; 34, 205–222. https://doi.org/10.1146/annurev.environ.030308.090351

101. Rudnick DR, Irmak S, Djaman K, Sharma V. Impact of irrigation and nitrogen fertilizer rate on soil water trends and maize evapotranspiration during the vegetative and reproductive periods. *Agricultural Water Management*, 2017; 191, 77–84. https://doi.org/10.1016/j.agwat.2017.06.007

102. Sadeji N, Madani H, Naderi A. Effect of Microelements and Selenium on Superoxide Dismutase Enzyme, Malondialdehyde Activity and Grain Yield Maize (Zea mays L.) under Water Deficit Stress. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 2011; 39, 153–159.

103. Schroeder JI, Kwak JM, Allen GJ. Guard cell abscisic acid signalling and engineering drought hardiness in plants. *Nature*, 2001; 410, 327–330. https://doi.org/10.1038/35066500

104. Shabani A, Sepaskhah AR, Kamgar-Haghighi AA. Growth and physiologic response of rapeseed (Brassica napus L.) to deficit irrigation, water salinity and planting method. *International Journal of Plant Production, 2013;* 28.

105. Shahnazari A, Liu F, Andersen MN, Jacobsen SE, Jensen CR. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. *Field Crops Research*, 2007; 100, 117–124. https://doi.org/10.1016/j.fcr.2006.05.010

106. Shiferaw B, Prasanna BM, Hellin J, Bänziger M. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Sec*, 2011; 3: 307–327. http://.doi.org/10.1007/s12571-011-0140-5

107. Smale M, Byerlee D, Jayne T. Maize revolution in sub-Saharan Africa. Policy Research working paper 5659, 2011. Washington DC: World Bank.

108. Srivastava AK, Mboh CM, Gaiser T, Ewert F. Impact of climatic variables on the spatial and temporal variability of crop yield and biomass gap in Sub-Saharan Africa- a case study in Central Ghana. *Field Crops Research*, 2017; 203, 33–46. **https://doi.org/10.1016/j.fcr.2016.11.010**

109. Stagl JC, Mayr E, Koch H. Effects of Climate Change on the Hydrological Cycle in Central and Eastern Europe, in: Managing Protected Areas in Central and Eastern Europe under Climate Change, *Advances in Global Change Research*, 2014; 31–43pp.

110. Stewart BA, Musick JT. Conjunctive use of irrigation and rainfall in semi-arid regions. *Advances in Agronomy*, 1982; 1: 1-23.

111. Tovihoudji GP, Improving maize productivity in Norhern Benin through localized placement of amendments and fertilizers. A thesis submitted for the obtention of the doctorate degree in agronomic sciences and biologic ingeneering in Université Catholique de Louvain, and doctorate degree in agronomic sciences at Université d'Abomey Calavi. 2018; 199p

112. Tsakmakis ID, Kokkos NP, Gikas GD, Pisinaras V, Hatzigiannaki E, Arampatzis G, Sylaios GK. Evaluation of AquaCrop model simulations of cotton growth under deficit irrigation with an emphasis on root growth and water extraction patterns. *Agricultural Water Management*, 2019; 213, 419–432. https://doi.org/10.1016/j.agwat.2018.10.029

113. United Nations Conference on trade and development (UNCTAD). Water for food, Innovative water management technologies for food security and poverty alleviation. 2011; 39pp.

114. UNEP. World Atlas of Desertification. The United Nations Environment Programme (UNEP), London, 1993.

115. Viala E. Water for food, water for life a comprehensive assessment of water management in agriculture. *Irrig Drainage Syst*, 2008; 22, 127–129. https://doi.org/10.1007/s10795-008-9044-8

116. Viechtbauer W. Conducting Meta-Analyses in R with the metafor Package. *Journal of Statistical Software*, 2010; 36, 1–48.

117. Waha K, Müller C, Rolinski S. Separate and combined effects of temperature and precipitation change on maize yields in sub-Saharan Africa for mid-to late-21st century. *Glob Planet Chang*, 2013; 106, 1-12

118. Wale A, Sebnie W, Girmay G, and Beza G. Evaluation of the potentials of upplementary irrigation for improvement of sorghum yield in Wag-Himra, North Eastern, Amhara, Ethiopia. *Cogent Food & Agriculture*, 2019; 5: 1664203 https://doi.org/10.1080/23311932.2019.1664203

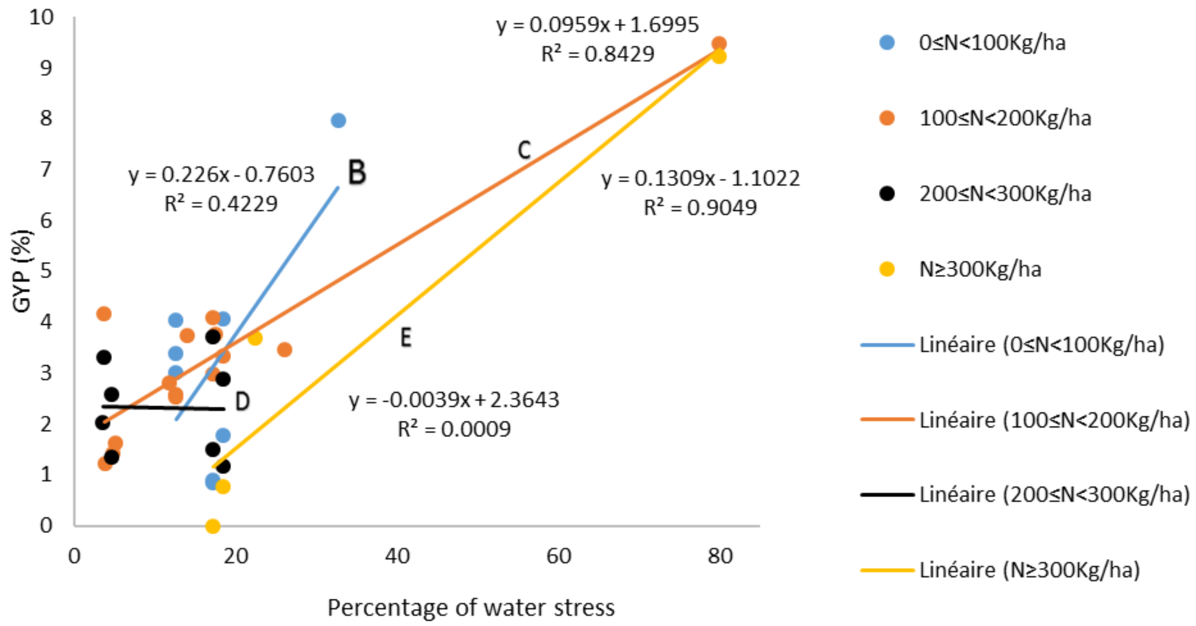
119. Yabi I, Afouda F. Extreme rainfall years in Benin (West Africa). *Quaternary International*, 2012; 262 39-43. http://.doi.org/10.1016/j.quaint.2010.12.010

120. Wang M, Zheng Q, Shen Q, Guo S. The Critical Role of Potassium in Plant Stress Response. *Int J Mol Sci*, 2013; 14, 7370–7390. https://doi.org/10.3390/ijms14047370

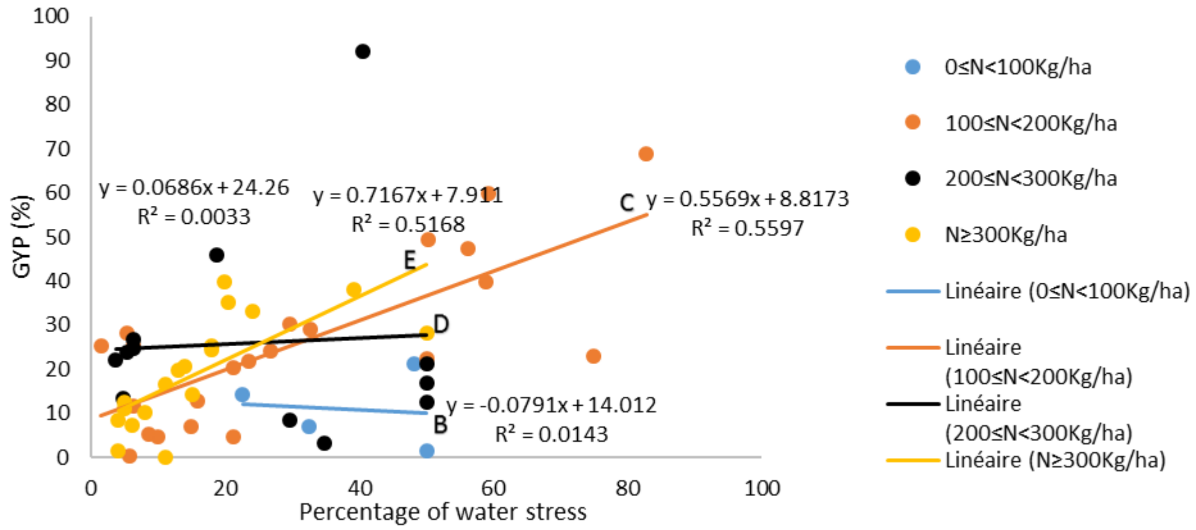
121. Zhang Y, Kendy E, Qiang Y, Changming L, Yanjun S, Hongyong S. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain *Agricultural Water Management*, 2004; 64 107-122. http://.doi.org/10.1016/S0378-3774(03)00201-4

122. Zwart SJ, Bastiaanssen WGM. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, 2004; 69, 115–133. https://doi.org/10.1016/j.agwat.2004.04.007.

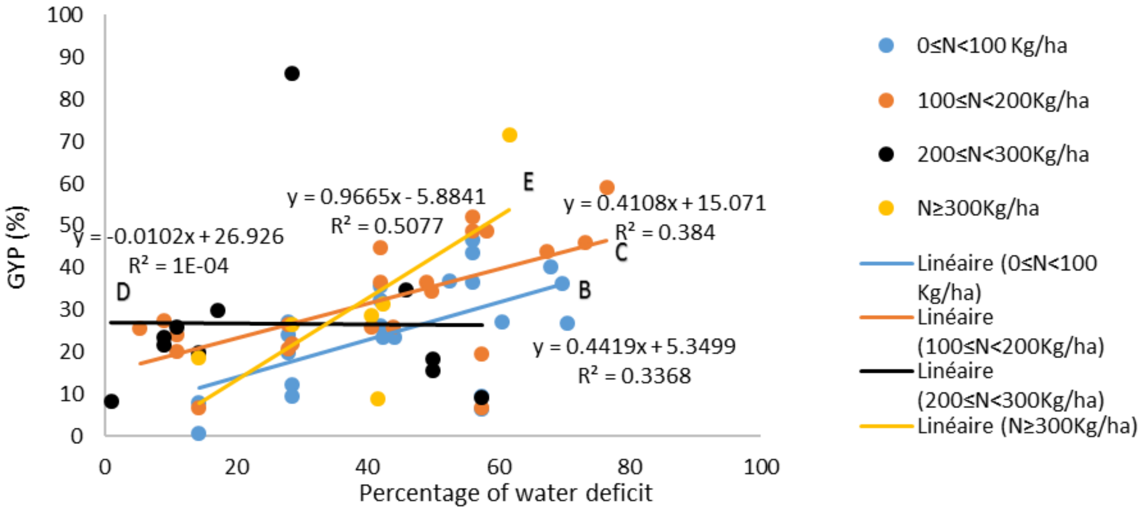
APPENDICES



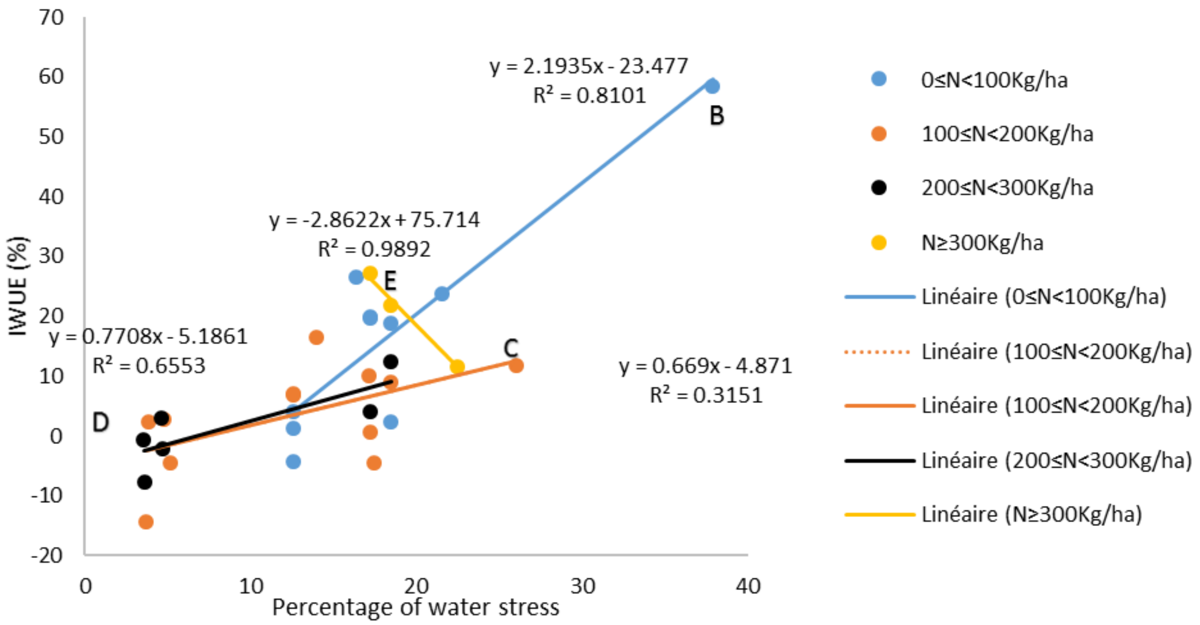
Appendice 1: Trend of maize yield under deficit irrigation and nitrogen rates when deficit is set at vegetative stage.



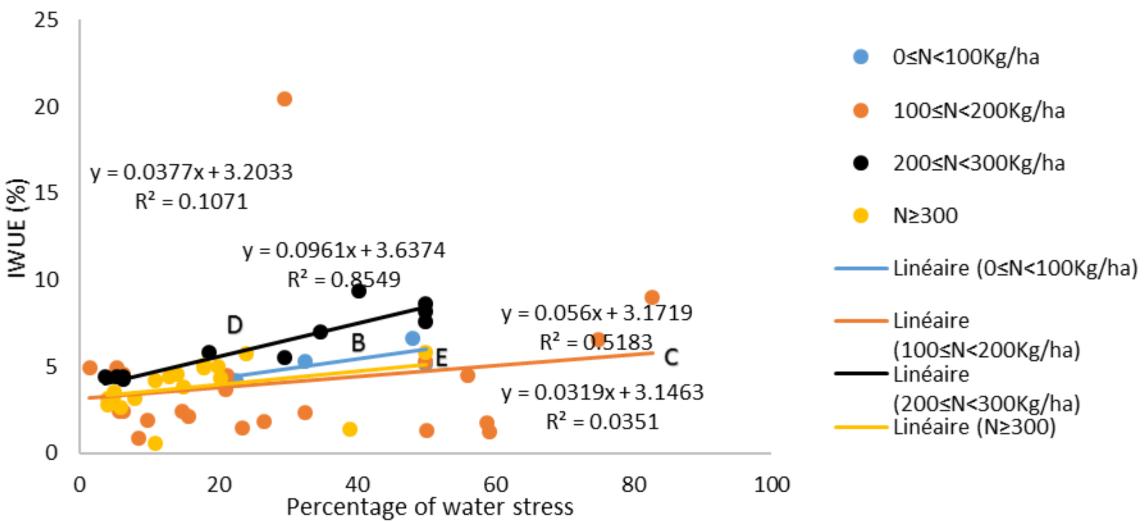
Appendice 2: Trend of maize yield loss under deficit irrigation and nitrogen rates when deficit is set at reproductive stage.



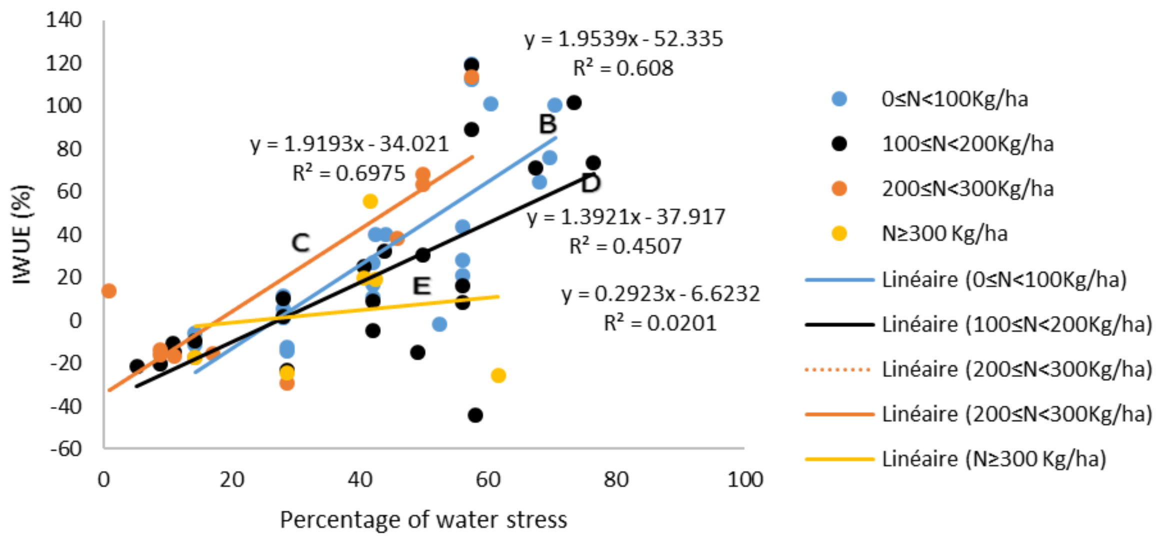
Appendice 3 : Trend of maize yield under deficit irrigation and nitrogen rates when deficit is set both at vegetative and reproductive stage.



Appendice 4: Effect of water stress and nitrogen rates on IWUE when water stress applied at vegetative stage.



Appendice 5 : Effect of water stress and nitrogen rates on IWUE at reproductive stage.



Appendice 6 : Effect of water stress and nitrogen rates on IWUE when water stress applied both in vegetative and reproductive stage.

Appendice 7: Anova results of grain yield of maize grown under supplemental irrigation, 2018

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
			Grain Yield		
Treatment	3	4900403	1633468	213.297	1.75e-06 ***
Bloc	2	16166	8083	1.055	0.405
Residuals	6	45949	7658		
			Stover Yield		
Treatment	3	8173615	2724538	223.102	1.53e-06 ***
Bloc	2	51615	25808	2.113	0.202
Residuals	6	73272	12212		

Appendice 8: Anova results of grain yield of maize grown under supplementary irrigation, 2019

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
			Grain Yield		
Treatment	3	12793407	4264469	51.339	0.000114***
Bloc	2	288179	144089	1.735	0.25
Residuals	6	498393	83066		
			Stover Yield		
Treatments	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Treatment	3	18290601	6096867	43.617	0.000181 ***
Bloc	2	1153649	576825	4.127	0.074597
Residuals	6	838696	139783		

Appendice 9: Anova results of Interaction effect of year and treatment on maize yield under supplemental irrigation, 2018-2019

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
			Grain Yield		
Treatment	4	16741334	4185334	78.904	2.53e-10 ***
Year	1	6625313	6625313	124.904	5.73e-09 ***
Treatment :Year	2	146089	73044	1.377	0.281
Résiduals	16	848692	53043		
			Stover Yield		
Treatment	4	31906751	7976688	60.28	1.91e-09 ***
Year	1	41497835	41497835	313.60	6.19e-12 ***
Treatment :Year	2	263725	131862	0.996	0.391
Résiduals	16	2117237	132327		

Appendice 10: Anova results of components of maize yield grown under irrigation deficit irrigation condition, 2019

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
			Harvest Index		
Treatment	3	0.0574	0.0191	39.225	0.000245***
Bloc	2	0.0055	0.0027	5.615	0.422
Residuals	6	0.0029	0.0004		
			Thousand grain yield (kg)		
Treatment	3	0.039	0.0103	54.632	9.51e-05***
Bloc	2	0.0001	0.0001	0.353	0.716
Residuals	6	0.0011	0.0002		
			Number of grain per cob		
Treatment	3	14654	4885	7.591	0.0182*
Bloc	2	2191	1096	1.702	0.2596
Residuals	6	3861	643		
			Grain Weight per Cob (g)		
Treatment	3	3566	1188.8	54.398	9.62e-05 ***
Bloc	2	123	61.7	2.822	0.137
Residuals	6	131	21.9		
			Number of full cobs plant^{-1}		
Treatment	3	5.9e-31	1.9e-31	1	0.455
Bloc	2	3.9e-31	1.9e-31	1	0.422
Residuals	6	1.1e-30	1.9e-31		
			Number of empty cobs per plants		
Treatment	3	4.667	1.556	9.956	0.00958**
Bloc	2	0.396	1.979	1.267	0.347
Residuals	6	0.937	0.1562		

Appendice 11: Anova results of grain yield and stover yield of maize grown under irrigation deficit irrigation condition, 2019

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
			Grain yield		
Treatment	3	7388686	2462895	56.519	8.62e-05***
Bloc	2	23917	11958	0.274	0.769
Residuals	6	261459	43577		
			Stover yield		
Treatment	3	11150270	3716757	14.359	0.00381**
Bloc	2	2053792	1026896	3.967	0.07983
Residuals	6	1553047	258841		

Appendice 12: Anova results of IWUE and WUE of maize grown under deficit irrigation condition, 2019

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
			IWUE		
Treatment	3	14.325	4.775	45.940	0.000156***
Bloc	2	0.119	0.060	0.573	0.592013
Residuals	6	0.624	0.104		
			WUE		
Treatment	3	9.323	3.1077	57.070	8.38e-0.5***
Bloc	2	0.073	0.0367	0.674	0.544
Residuals	6	0.327	0.0545		