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)

REPUBLIQUE DU MALI

Un Peuple - Un But - Une Foi

Defended on: 01/02/2020

DOCTORATE THESIS

ASSESSMENT OF LOSS AND DAMAGE INDUCED BY WATERLOGGING AND SUBMERGENCE STRESS IN MAIZE UNDER TYPICAL AMBIENT CONDITIONS OF THE WEST AFRICAN SAHEL

A THESIS 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

UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

By

Elidaa Kossi DAKU

JURY

President: *Dr Alassane MAIGA, Associate Researcher, IER, Mali*

Members
Examiner: *Dr Sabake DIARRA, Associate Professor, IPR- IFRA, Mali*
Examiner: *Dr Maïmouna TRAORE, Senior Lecturer, IPR- IFRA, Mali*
Reporter: *Dr Souleymane Sidi TRAORE, Senior Lecturer, FHG-USSGB, Mali*
Director: *Dr Seyni SALACK, Senior Researcher, WASCAL CoC, Burkina Faso*
Co-director: *Dr Nadine Omonlola WOROU, Agronomist Modeller, ICRISAT- WCA, Mali*

Assessment of loss and damage induced by waterlogging and submergence stress in maize under typical ambient conditions of the West African Sahel

Thesis in the Rural Polytechnic Institute of Training and Applied Research in partnership with West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), submitted

in

Partial fulfilment of the requirements

for the

Degree of Doctor of Philosophy in Climate Change and Agriculture

of the

University of Sciences, Techniques and Technologies of Bamako (USTTB)

February 2020

by

Elidaa Kossi DAKU

Declaration

I, Elidaa Kossi DAKU, declare that this PhD Dissertation entitled “Assessment of loss and damage induced by waterlogging and submergence stress in maize under typical ambient conditions of the West African Sahel” is my own work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at the University of Sciences, Techniques and Technologies of Bamako or to any other institutions.

Signature : ……………… Date : ……………….

Name: *Elidaa Kossi DAKU*

This thesis has been submitted for examination with our approval as supervisors

1. *Dr Seyni SALACK, Senior Researcher, WASCAL Competence Center, Burkina Faso (Main Supervisor)*

Signature : ……………… Date : ……………….

2. *Dr Nadine Omonlola WOROU, Agronomist Modeller, ICRISAT- WCA, Mali (Co- Supervisor)*

Signature : ……………… Date : ……………….

3. *Dr Yacouba Diallo, Coordinator of WASCAL Graduate Program on Climate change and Agriculture, IPR-IFRA, Mali*

Signature : ……………… Date : ……………….

Table of contents

Dedication

With unfailing love this thesis is dedicated to:

(1) My virtuous wife and sons – Gnimtou, Samuel and Isaiah, for having flooded me with love, patience, understanding throughout my graduate program. I love you!

(2) My precious parents - Mr. and Mrs Eli K. DAKU, for their prayers and entire efforts to ensure to us a good education. I hope to copy your courage and faith in a bright future for your children.
Thank you Mum and Dad!

(3) My brother, Dogbeda Daku, who I lost during my graduate studies.
My children will never experiment the expression of your love.
I wish you perfect rest in peace.

Acknowledgements

Above all, I give my thanks to the living God and my saviour, Jesus Christ, for transforming me during my graduate program. Incredible experience is to feel your love, help, strength, protection and your inspiration. “The LORD, your God, is with you. He is strong. He will save you. He will be very happy about you! He will quietly love you. He will sing, because he is so happy about you!” (Zephaniah 3:17).

Several persons have contributed so much to my doctoral studies and I wish to express my consideration to all of them. I thank my main supervisor, Dr Seyni Salack, who considering me as his young brother and provided me his careful guidance which leads to this thesis despite various and tremendous obstacles. I learnt from him that “Research is difficult, but, it increases certain characters that make a huge difference in life: love, passion, determination and tenacity”. I remain always grateful to him for all his assistance. I am proud to have been his PhD student. Sincerely thank my co-supervisor, Dr Nadine Omonlola Worou, who trained me in crop modelling, provided me a scholar visit opportunity at the International Crops Research Institute for the Semi-Arid Tropics - Bamako and contributed in no small way to carefully guiding my research. Several times, she was angry with some of my behaviours, but she continuously provided to me, alternatives for overcoming many challenges. If I have to summarized what I learnt from her. It would be: “You must give more value what you have accomplished”. May God bless her!

I also appreciate the continuous advices from Dr Adambounou Amouzou since the early stage of my field work; the interest of Dr Mawuli Amegadje for the progress of my work. Special thanks to Dr Safietou Sanfo, who associated me to Green Builders project and give me the opportunity to gain experience in the use of urban waste in urban agriculture.

I am grateful to all the persons that help me in my field data collection: (i) Ms Nadege Dossoumou and Ms Namo Lawson-Zankli, may you succeed in your PhD programs; (ii) Ms Aïda Ganaba (who I surname Ms Aïdara) for her friendship and for all she have done for me; (iii) Mr Samuel Guug and his team mates Mr Michael Ayamba, Mr Michael Tiikah, Mr Kwesi and Mr Ben. I thank for your magic ideas and the interesting collaboration; (iv) Dr Inoussa Saley; Mr Zakari Traore and Mr Koufanou Hein. Thank you; (v) Thank you, Mr Amine Sawadogo, who gave me too many moments of headache but also many moments of laugh. I enjoyed to work with you.

I thank all the WASCAL Competence Team members for their support which made my research work possible in Burkina and Ghana. I don't forget the staff of the International Crops Research Institute for the Semi-Arid Tropics – Bamako, especially Mr Antonio Edoh.

My work could not have been done without several brothers and friends who assisted me in various ways by sharing their love, time and prayers. I thank: (i) Mr Gilbert Buagbe and his wife for theirs precious praying for me and my family members. Thanks and God bless you! (ii) Mr Didi Daku, my brother who supported me with his love, messages and prayers. I am very grateful. May God continuous to accomplish miracles in your life; (iii) Ms Dédié Daku for all the voice message sent to me; (iv) Ms Patience De-Souza, Ms Eyram Ogbletsan, Ms Rose-Caroline Anyla and Ms Yvonne Daku for all their love for me and my little family; (v) my little and lovely niece, Emmanuela Benonia Daku for all the songs she sent to me via her mother' phone. In few years you will read these words. I love you!; (vi) my parents-in-law, Mr. and Mrs Koro, to have assisted my wife, children and my parents during the difficult moments. I am very grateful.

I thank all of my friend including Mr Tiyakantob Nehanke and his wife, Mr Ebelaba Atcholé-Kezie, Mr Laté Tété and Mr. Pedro Fiakli for all their support and help during critical periods. For my classmates who showed me much love for which I am thankful, I wish to meet you soon, at high position of research centre or donors.

This work was funded by the German Federal Ministry of Education and Research (BMBF) through the West African Science Centre for Climate Change and Adapted Land Use (WASCAL). Authors also acknowledge partial co-funding was from APTE-21/FSP-AGRICORA project (MEAE/IRD, AGRICORA axe 1, convention 2016–2018) and, the UPSCALERS project (Grant AURGII-1-074-2016) which is part of the African Union Research Grants financed through the Financing Agreement between the European Commission and the African Union Commission (DCI-PANAF/2015/307-078). The content of this thesis is the sole responsibility of the author and can under no circumstances be regarded as reflecting the position of the African Union Commission or European Union Commission.

List of acronyms and abbreviations

°C: Celsius degree

ACC: 1-Amino-cCyclopropane-1-Carboxylic acid

AgMIP: Agricultural Model Inter-comparison and Improvement Project

AOA: Amino eth-Oxy-Acetic acid

APSIM: Agricultural Production Systems sIMulator model

AS: Aeration Stress

AVG: Amino ethoxy-Vinyl Glycine

CAF: Critical Aeration Factor

CIMMYT: International Maize and Wheat Improvement Center

cm: Centimeter

CO_2: Carbon dioxide

CSIR-CRI: Crop Research Institutes of Kumasi

CSIR-SARI: Crop Research Institutes of Tamale

CS_j : Normalized crop susceptibility factor for stage j

DAS: Days After Sowing

DTO: date-of-occurrence

EPIC: Environmental Policy Integrated Climate

FAO: Food and Agriculture Organization of United Nations

GMHU: Heat Units required for Germination

ha: Hectare

HC: Hydraulic Conductivity

HI: Harvest Index

IITA: International Institute of Tropical Agriculture

IPCC: Intergovernmental Panel on Climate Change

Kg: Kilogram

LAI: Leaf Area Index

LAIMX: Maximum Leaf Area Index

m: Meter

MCP: Methyl-Cyclo-Propene

MCS: Mesoscale Convective Systems

MDA: Malondialdehyde

MFG: Meteosat First Generation

mg: Milligram

mm: Millimeter

Mn: Manganese

MRE: Mean Relative Error

MSG : Meteosat Second Generation

NPK:

Fe

PET: Potential evapotranspiration

PHU: Thermal time

PO_1: Porosity minus field capacity of the top 1 m of soil in mm

PVC: Poly-Vinyl Chloride

RMSE: Root Mean Root Square Error

RYL: Relative Yield Loss

SAT: Saturation

SDI: Stress Day Index

SEW30: Excess water stress-day factor

SSDI: Simulated stress day index

SSEW: Simulated Excessive Water Stress Factor

ST_1: Water content minus field capacity of the top 1 m of soil in mm

TB: optimal temperature

USA: United Stated of America

WA: biomass-energy conversion factor or Radiation use efficiency

WRB: World Reference Base for soil resources classification systems

WTDi: Daily water table depth (cm)

List of figures

List of tables

Résumé

Le climat du Sahel ouest-africain, changeant en raison du réchauffement globale, les systèmes agricoles sont confrontés à un stress d'excès d'eau induit par les pluies diluviennes. Notre première expérimentation, implémentée dans la banlieue de Ouagadougou (Burkina Faso), a testé, dans des conditions naturelles en plein champ, durant deux années, les effets de différent niveau de lames d'eau surnageant le sol (2-3 cm et 7-8 cm au-dessus du sol) et leur stagnation (1 à 3 et 3 à 6 jours) sur la croissance, le développement et la productivité du cultivar de maïs, *Obatampa*, à trois de ses stades de développement (stade à six feuilles (V6), épiaison (VT) et le stade grain laiteux (R3)). L'hypoxie (1 à 3 jours de saturation du sol) et l'anoxie (4 à 6 jours de saturation du sol) au stade épiaison, ont réduit respectivement, le rendement en grains de 53% et 54%. Au stade V6, seule l'anoxie provoquait 31% de perte de rendement en grains. Ces pertes de rendement en grains étaient exponentiellement corrélées à l'indice des jours de stress (SDI) (R^2 = 0,7 considérant tous les stades phénologiques). La deuxième expérimentation réalisée en plaine inondable à Aniabisi (nord-Ghana), a testé l'effet cumulé de l'engorgement fréquent provoqué par les précipitations, à différentes localisations topographiques des parcelles (haut de pente, milieu de pente et bas de pente), associées aux techniques de gestion de l'eau (présence ou absence de diguettes) et à deux dates de semis du cultivar de maïs, *Wang Data*. Il ressort que l'effet cumulé de l'engorgement lorsqu'il se produisait depuis le stade végétatif jusqu'à la fin du cycle de la culture pouvait réduire drastiquement la croissance et la productivité du maïs. Les pertes de rendement en grains sur les parcelles en bas de pente représentaient donc 91% (en 2017) et 62% (en 2018). Dans ces conditions, une forte relation exponentielle (R^2 = 0,8) a été déterminée entre les pertes de rendement en grains de *Wang Data* et le facteur de stress d'excès d'eau (SEW30) au stade végétatif. Ce facteur pourrait être utile comme outils d'évaluation des pertes et des dommages ou intégrer les schémas d'assurances agricoles indicielles. Le calibrage et la validation du modèle de culture EPIC, se basant sur les deux expérimentations a permis de bien simuler les périodes d'engorgement du sol au cours desdites expérimentations. Des indices générés à partir de l'humidité du sol simulée semblent être de bon prédicteur de baisse de rendement grains durant le stade de l'épiaison d'*Obatampa*. Le modèle EPIC était néanmoins limités pour simuler les baisses de rendement, due à une anoxie au stade V6, au stade VT, ou fréquent dès le stade végétatif. L'amélioration du modèle EPIC devra nécessiter l'incorporation de différentes sensibilités à l'engorgement par stade phénologique.

Mots-clés: Maïs, Engorgement, Indice de stress, Simulation, Sahel Ouest- Africain

Abstract

As the climate of the West African Sahel changes due to global warming, agricultural systems are facing stress due to the excess water induced by extreme rain events. Our first experiment, implemented in the suburbs of Ouagadougou (Burkina Faso), tested, the effects of different water levels above the soil surface (2-3 cm and 7-8 cm above ground) and their stagnation (1 - 3 and 3 - 6 days) on the growth, development and productivity of *Obatampa* maize cultivar, at three of its growth stages (stage at six leaves (V6), tasseling (VT) and the milky grain stage (R3)) during two years, under ambiant on-farm conditions. Hypoxia (1 to 3 days of soil saturation) and anoxia (4 to 6 days of soil saturation) at the tasseling stage reduced the grain yield by 53% and 54% respectively. At V6 stage, only anoxia caused 31% grain yield loss.Those grain yield losses were exponentially correlated with the stress days index (SDI) (R^2 = 0.7 considering all the growth stages). The second experiment was carried out on the floodplain of Aniabisi (northern Ghana). The cumulative effect of the frequent waterlogging caused by precipitation, at different topographic locations (upslope, middle slope and downslope), associated water management techniques (presence or absence of bunds) and two planting dates for the *Wang Data* maize cultivar was tested. The results showed that the cumulative effect of waterlogging when it occurs from the vegetative stage to the end of the crop cycle can reduce the growth and productivity of maize drastically. Grain yield losses on downslope plots, represented 91% (2017) and 62% (2018). Under these conditions, a strong exponential relationship (R^2 = 0.8) was established between the grain yield loss of *Wang Data* and the excess water stress factor (SEW30) in the vegetative stage. This factor could be useful as tool for assessing losses and damages associated with hazards due to excess rain events and also as tool in crop insurance scheme. By using the experiments for the calibration and validation of the EPIC model, it simulated well, the periods of waterlogging during these experiments. Indices generated from the simulated soil moisture appear to be a good predictor of grain yield decline during the tasselling stage of *Obatampa*. Nevertheless, the EPIC model was limited to simulating the reductions of yield, due to temporary waterlogging greater than 3 days at the V6 stage, occurring at the tasseling stage, or frequent from the vegetative stage. The improvement of the model should require the incorporation of different sensitivities to waterlogging at phenological stages.

Keywords: Maize, Waterlogging, Stress index, Simulation, West African Sahel.

.

1. General Introduction

1.1. Rationale

Under global warming, rainfall variability has increased over the West African Sahel. Beside the erratic intra-seasonal distribution of rainfall events leading to a mixed pattern of the rainfall regimes (Salack et al., 2016), the amplitude and the frequency of heavy rain has increased significantly (Ly et al., 2013; Taylor et al., 2017; Salack et al., 2018; Bichet and Diedhiou, 2018), showing a glimpse of what the future rainfall regime may look like. According to climate model projections, by the mid-twenty-first century, the number of heavy rain events may likely increase in the region (Vizy and Cook, 2012; Sylla et al., 2015; Taylor et al., 2017), bringing a more challenging situations to rain-fed cropping systems crop management, to smallholder farmers' income and the low infrastructure of subsistence farming system (Sanfo et al., 2017). Across the literature, the documented abiotic constraints for a staple crop such as maize (*Zea mays L.*), in the West African Sahel are low soil fertility and drought (Badu-Apraku and Fakorede, 2017). However, the stress due to excessive soil moisture (soil waterlogging) and water stagnation is less treated, although it is one of the most serious constraints capable of affecting lowland cereal crops' growth, development and production (Ren et al., 2014; Jaiswal and Srivastava, 2015). Heavy rain events are the most common causes of water stagnation, waterlogging of shallow soils, erosion of arable land in high runoff areas, fungal infestation of some crop leaves and roots (Rosenzweig et al., 2001; Salack et al., 2015) and soil nutrients leaching (Guan et al., 2015). The land area already affected by waterlogging is lower than in Asia (Lavigne et al., 1996), but the risk exists and is growing in certain areas of sub Saharan Africa (Cairns et al., 2012; Salack et al., 2018).

Commonly used adaptation measures include crop diversification, mixed crop-livestock systems, tolerant crop varieties and other water and soil conservations techniques: Zaï, half-moon, stone bunds (Zougmoré et al., 2014; Sanfo et al., 2017). Crop insurances are the non-structural methods used to protect farmers against weather-based risks such as extreme rain events. However, crop insurance systems used in West Africa are limited. Very often, these crop insurance do not account for damages and yield losses due to water stagnation and/or temporary flooding (Sarr et al., 2012). They tend to focus on drought and use aggregate yield indices to focus on drought and use aggregated yield index (Sarr et al., 2012; Muller and Leblois, 2013), which could hide disparities at small scale (Leblois et al., 2014). Also, apart from drought and dry spells risk factors (Alhassane et al., 2013; Salack et al., 2014), West African smallholders are increasingly facing frequent intense rain events. In the actual, context of global warming, the effects of intense rainfall on crop production could be worst, when they are combined with warmer temperatures, since flooding damage can increase with a rise in temperature (Fausey and McDonald, 1985; Nielsen, 2019).

1.2. Literature Review

1.2.1. Trend and variability of heavy rainfall over West African Sahel

As the climate of the West African region is changing, a new pattern of rainfall variability has emerged since the 1990s (Nicholson, 2005; Olsson et al., 2005; Lebel and Ali, 2009), characterized by a mixture of intense rainfall (Giannini et al., 2013; Panthou et al., 2014; Maidment et al., 2015), long dry spells (Salack et al., 2014; Sarr et al., 2015) and sequences of floods events (Panthou et al., 2014; Zahiri et al., 2016). As stated, in Salack et al. (2018), heavy rains and flooding affected 600,000 people across West African countries in September 2009. The worst hit countries were Burkina Faso, Senegal, Ghana and Niger (Di Baldassarre et al., 2010). In Burkina Faso, those rain events induced losses estimated at almost 8 billion FCFA for the smallholder's farmers, including 6 billion FCFA as losses due to complete or partial submersion of 22,200 ha. On the flooded area, sorghum and maize were the most affected with respectively 14.8 % and 8.6 % of total flooded surface (World Bank, 2010). Almost 1.7 million people were affected by floods in Benin, Burkina Faso, Chad, Ghana, Niger, Nigeria, and Togo in 2010 (Sarr, 2011) and according to FAO, this year rainfall pattern had significantly improved, the food supply but also caused serious flooding that damaged over 141,000 hectares of cereal crops and cash crops in Benin, Chad, Burkina Faso, Niger, Gambia, Ghana, Guinea, Mali, Senegal and Sierra Leone (FAO, 2011). In 2012, more than 80% of Nigeria was affected by heavy rains which submerged much of Delta and Bayelsa states in the southeast.

The cumulative rainfall of extremely wet days and the maximum number of consecutive wet days have been increased significantly, since the late 1980s, indicating that extreme rainfall events have become more frequent in the West African Sahel during the last decade (Figure 1.1 and Figure 1.2).

In addition, IPCC (2013), projected an increase of frequency and intensity of heavy rainfall events in the Sahel. By the mid-twenty-first century, climate projections suggest an increase in the number of heavy rain days over West Africa and the southern Sahel, respectively by 40%-60% and by 50%-90%. Precisely, the extreme rainfall intensity could be increased by 10%-25% over Senegal, southern Mali, Burkina Faso, northern Nigeria, and southern Chad (Vizy and Cook, 2012; Sylla et al., 2015).

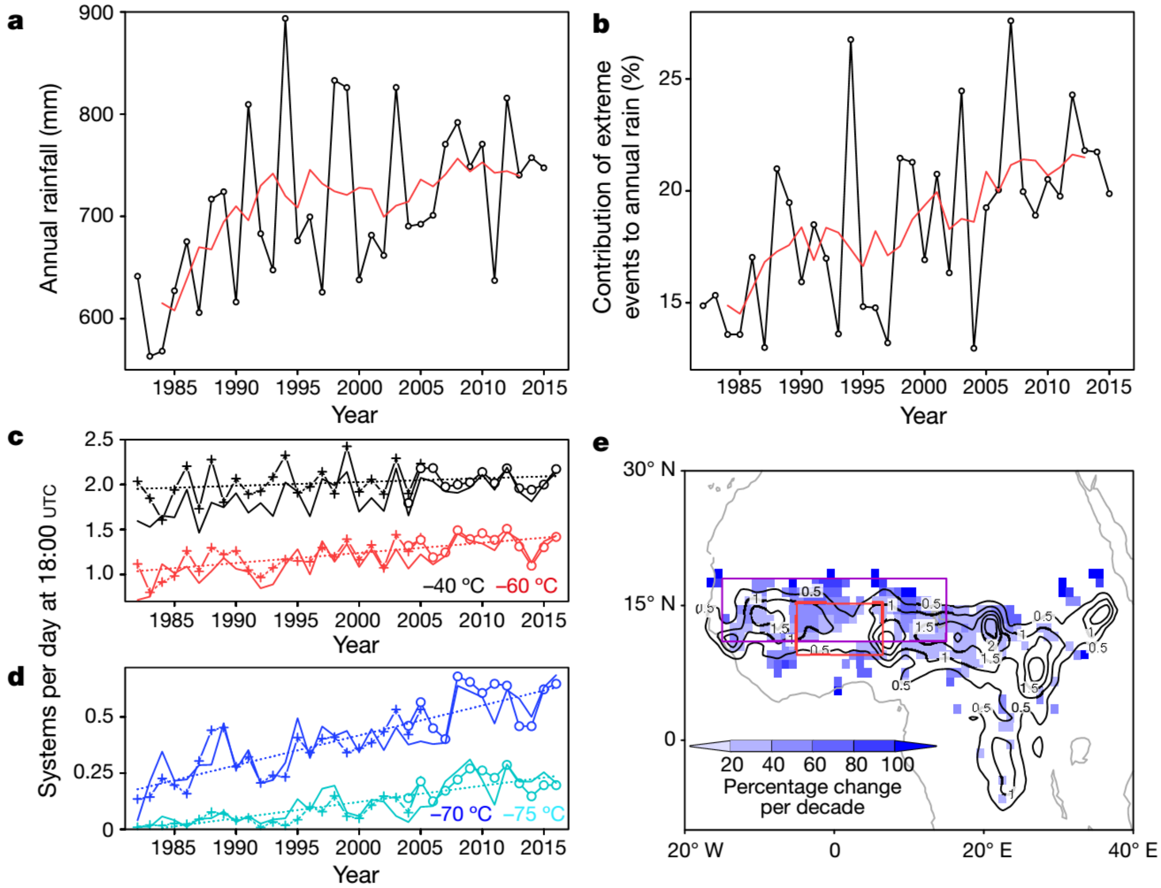


Figure 1.1. Trends in mesoscale convective systems (MCS) and annual rainfall (a), and extreme events contribution to annual rainfall (b). Red lines indicate five-year running means. Regional MCS frequency at 18:00 utc at different temperature thresholds, derived directly from measurements onboard the Meteosat First Generation (MFG; + symbols) and Meteosat Second Generation (MSG; o symbols) satellites. Dotted lines denote significant trends (P < 0.05)(c, d) in MCS at 18:00 utc. Trends are expressed as a percentage change per decade, relative to the 35-year mean (contours) (e) *(Taylor et al., 2017).*

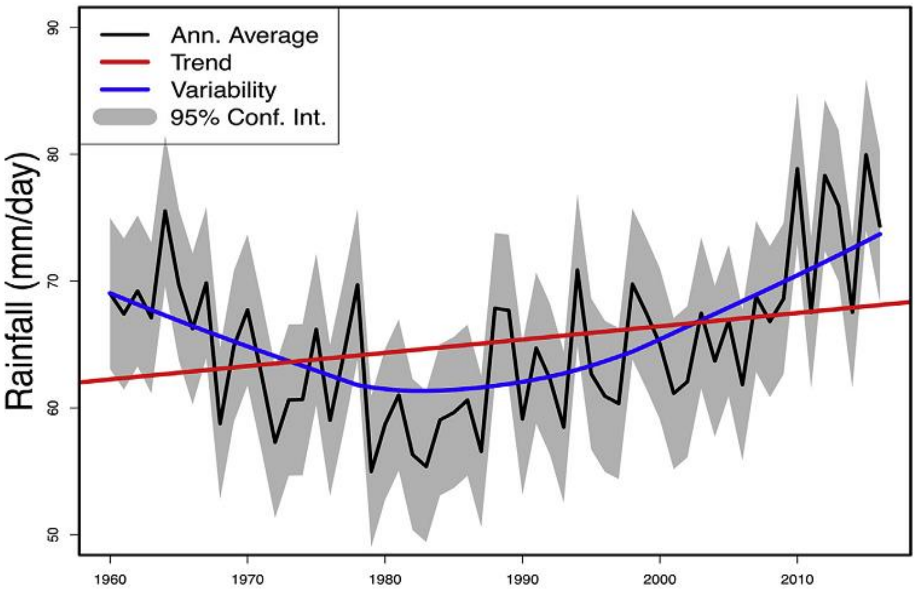


Figure 1.2. Inter-annual variability of 99th percentile thresholds of intense rainfall events depicted from 72 stations distributed over the Sahel (Salack et al. 2018)

In this region, heavy rainfall events contribute ∼50–90% to the seasonal rainfall amount with a South-North gradient (Ta et al., 2016). This inhomogeneous distribution and the nested land-atmosphere phenomena involved in the formation of convective systems makes it difficult to classify rainfall from the event scale of minutes-to-24-hours (Mathon et al., 2002; Zahiri et al., 2016). Delving through multiple sources of observation uncertainties, of integrated sources of rain gauge data, Salack et al. (2018) identified three scales for rating heavy rainfall into category 1, 2 and 3. The categories 1 and 2 occur most likely between week 27 and 35 of the year with an accumulated daily amount waving across 37-65 mm for category 1 and less or equal to 85 mm/day for category 2. The daily accumulated rain rate of category 1 has 52% probability of occurrence against 40% probability for category 2, within the same period. When a heavy rainfall event of category 1 (category 2) is observed or predicted, a yellow (orange) colour flag is suggested in operational warning. The rain rates of category 3 is identified when more than 85 mm/day, occurring between the 28^{th} and 38^{th} week of the year. It is the most damaging class of heavy rains but very difficult to predict. For operational warnings, heavy rain events of category 3 is flagged with red colour denoting highest level risk of flooding or damages. The timing of the three categories of heavy rain events falls within three phases of the West African monsoon namely the installation phase (July), the intensification phase (August) and the retreat phase (September). Category 1 is observed in the installation phase over central sub-regions after the abrupt monsoon jump (Sultan and Janicot, 2003) while categories 2 and 3 are recorded in the intensification and retreat phases respectively. In these last two phases, rainfall intensity is characterized by a steady increase until it reaches its maximum at the end of August (also known as the continental phase of West African monsoon) and an abrupt retreat in one month, with residual rainfall in October (Lebel and Ali, 2009). The spatial distribution of date-of-occurrence (DTO) of Category 2 and 3 suggests an east-west bipolar pattern while category 1 is unevenly observed all over the region. All categories are recorded with a time lag of at least one week and the western Sahel is predominantly influenced by the occurrence of categories 2 and 3 in September. The distribution of DTO also exhibits a coherent sub-regional high risk zones of local extreme rainfall. These conclusions are detailed in Lawson-Zankli (2018) and Salack et al. (2018).

1.2.2. Effects of extremes rainfall, and soil waterlogging on farming systems

In these arid and semi-arid regions of West Africa, heavy rain events are important sources of havoc for life and property and also important sources of water bodies used for multiple purposes including domestic, irrigation, fishing, livestock breeding etc. Heavy rain events are the sources of flooding, on-farm water stagnation and waterlogging of shallow soils and the small holder farming systems, waterlogging affects also field management activities. The delay of farming operations (tillage, weeding and fertilisation) and the profusion of water-loving weeds are often the effect of excessive soil moisture. The soil physical, chemical, electro-chemical and biological characteristics also is altered. Intensive rain events and waterlogging cause soil compaction, increased bulk density, massive structural changes through runoff, oxygen depletion, CO_2 accumulation and a lowered diffusion coefficient of gases (Glinski, 2018; Ferronato et al., 2019; Manik et al., 2019). Waterlogged soil warms up slowly and lower soil temperature restricts root development, depresses biological activity in the soil resulting in lowered rate of nitrogen, thereby, hampering seed germination and seedling growth. The reduction of soil temperatures; results in stunted growth and reduced production of nitrogen.

Under waterlogging, the soil faced the reduction of the mineralisation processes and aerobic microbial activity. Certain nitrifying microorganisms cannot survive under oxygen deficit, resulting in reduced microbiological activity (Jaiswal and Srivastava, 2018; Nguyen et al., 2018) and depleted soil Nitrogen availability (Laanbroek, 1990). Waterlogging also induces electrochemical changes by decreasing redox potential and excess electron changes, in order to produce Fe^{2+} and Mn^{2+} which are harmful to most food crops (Worou et al., 2012; Aldana et al., 2014; Sharma et al., 2018; Manik et al., 2019). In addition, metabolites such as phenolics, volatile fatty acids and ethylene are also injurious in the rhizosphere (Shabala, 2011; Coutinho et al., 2018). Acidity of waterlogged soil can be reduced by the accumulation of volatile organic acids as well as the high concentration of CO_2 (Greenway et al., 2006). Soil salinity can also increase in the root zone, when water from lower soil layers which may contain salts (sodium) is brought up to the soil surface by capillary rise or water table rise and create alkaline conditions.

1.2.3. Losses and damages due to excessive water, waterlogging on crop production

Waterlogging stress, leads to the crop yield reduction which is negatively correlated with the level of the stress (Culati et al., 2000; Zhu et al., 2005). Moreover, the sensitivity to waterlogging stress vary according to the crop. Cotton yield can be reduced by 10.6%, 19.7% and 42.2%, respectively after 1 day, 3 days and 5 days of flooding (Zhu et al, 2003). Sesame, tobacco, and leguminous crops have no resistant character to waterlogging, and could lose a lot of flowers and pods after a short time flooding. However, crops as cotton can quickly resume after short period flooding. There is also different sensitivity to waterlogging stress per growth stage. In most cases, the crop sensitivity to waterlogging at middle growth stage, is higher than at earlier growth stage. The sensitivity at reproductive stage, is higher than at vegetative growth stage, and at the earlier stage of flowering and grain formation exceeds the later stage sensitivity. For some crops, at flowering or podding stage, flooding can lead to flowers and pods abscission, which sharply reduce the yield. However, the same degree of waterlogged stress on earlier stage seems to have a little effect on the yield (Bange et al., 2004; Milroy et al., 2009).

Maize crop is more susceptible to waterlogging from the early seedling stage to the tasselling stage (Mukhtar et al., 1990; Rosenzweig et al., 2002; Rao and Li, 2003; Liu et al., 2010). From experiments in China, Li et al. (2011), have shown that more than 3 days of waterlogging can decrease yield by 40%. For Tian et al. (2019), maize yield can decrease by 65 - 80% with 9 days of waterlogging at seedling stage but there are no significant adverse effects at the tasselling stage. In the other hand, Yang et al. (2016), found that, around flowering stage, grain yield can be suppressed as a result of shortened grain filling duration.

1.2.4. Increasing pressure on lowlands use for agriculture

Estimated between 2% and 5% of West African land (11 to 16 million hectares), lowlands are exposed to excessive moisture or waterlogging (Blein et al., 2008). However, because of their fertility and their ability to conserve soil moisture, they are considered to be an interesting alternative against the increasing pressure applied on uplands and recurrent dry spells in West Africa (Lavigne et al., 1996), without take into account the risks related to excessive water during heavy rain events or wet spells. For example, in northern Ghana, where maize, sorghum and rice are the main crops, nearly 60% of exploited land is exposed to frequent waterlogging (Cairns et al., 2012).

1.2.5. Possible solutions for reducing the effects of waterlogging and their limitations

Practices used to alleviate the effects of waterlogging in cropping systems were classified into soil and crop management practices which soil management practices include, surface drainage which is the easiest practice but the open drain reduced the available cropping area and periodic maintenance is needed for insuring the drain function (Ritzema et al., 2008; Ayars and Evans, 2015; Palla et al., 2018). Raised bed system improves the soil structure but in addition to the reduction of cropping area, the weed control in the furrow is complex and its efficiency depend on the height of water table in case of flooding (Acuña et al., 2011; Gibson, 2014). Pipe drains are well tested method for severe waterlogging but this technic is expensive and not affordable by smallholder's farmers. Moreover, its long-term efficiency needs an outfall and periodic maintenance (Filipovic et al., 2014; Teixeira et al., 2018). Vertical drainage is also adequate for severe waterlogging but its maintenance and operational cost are higher than for pipe drainage systems (Kijne, 2006; Prathapar et al., 2018). Mole drains is cheaper than other underground drainage technics but cannot maintain its integrity in dispersive soils (Tuohy et al., 2018; Dhakad et al., 2018). Controlled traffic farming can reduce soil compaction, erosion, tillage costs, water and nutrient losses but its efficiency changes under different field conditions, such as different crops, soil types and tillage (Guenette and Hernandez-Ramirez, 2018; Bennett et al., 2019). Strategic deep tillage and subsoil manuring decrease soil strength resulting in deeper and denser rooting but without regular amendment, its efficiency is shortened and decrease under acid, sodic or saline sub-soils (Roper et al., 2015).

For crop management practices in waterlogging conditions, early sowing and choice of vigorous crop takes advantage of early-season soil moisture as buffer and avoids late season terminal waterlogging events. This option provides minor benefit in case of severe waterlogging (Ploschuk et al., 2018; Sundgren et al., 2018; Wollmer, 2018). Bio-drainage or bio-pumping through the incorporation of deep rooted and herbaceous perennial legumes adapted to waterlogging into cropping systems can reduce soil waterlogging by the natural absorption of water on greater depths than most annual crops and high transpiration (McCaskill and Kearney, 2016; Nichols, 2018). Tested at many locations with success, it needs proper plantation techniques, expertise in the choice of plants (the perennial legume and annual crop) and regular maintenance operations (thinning, pruning, and harvesting) (Lerch et al., 2017; Muñoz-Carpena et al., 2018; Sarkar et al., 2018; Singh and Lal, 2018). Nutrient deficiency is one of the major effects of waterlogging on crop. Thus, nutrient application (nitrogen in particular), improves plant growth and development but appropriate application methods, nutrient types, timing and rate should be considered to avoid any negative effect (Najeeb et al., 2015; Pereira et al., 2017; Kaur et al., 2018; Huang et al., 2018) and nutrient imbalance on soil ecology (Rochester et al., 2001; Jackson and Ricard, 2003). The ability to predict waterlogging events (variable according to seasons) and therefore the crops' demand also limits the effectiveness of fertilizers and therefore raises the question of whether highly available N applications would be preferable when waterlogging limits growth (Lubkowski and Grzmil, 2007; Trenkel, 2010). Plant growth regulators may mitigate waterlogging damage of plants by applying at the appropriate growth stage by promoting stomatal conductance and photosynthetic capacity of waterlogged plants. However, due to inconsistent results there has been little diffusion of these regulators to alleviate waterlogging damage. Moreover, appropriate methods, timing and rate should be considered for large-scale application (Habibzadeh et al., 2012; Ren et al., 2016; Ren et al., 2018; Wu et al., 2018). Use of anti-ethylene agents such as 1-methylcyclopropene (1-MCP), amino ethoxyvinyl glycine (AVG), 1-aminocyclopropane-1-carboxylic acid (ACC), amino ethoxyacetic acid (AOA), silver and cobalt ions, have been reported to inhibit the synthesis or accumulation of ethylene through blocking the biosynthetic pathway (Najeeb et al., 2017; Vwioko et al., 2017) of ethylene (McDaniel and Binder, 2012). This option can increase both photosynthesis and yield by diminish crop loss induced by ethylene accumulation under waterlogging conditions. But, it is untested at broad scale agriculture (Shabala, 2011; Najeeb et al., 2018). Pre-treatment with hydrogen peroxide may protect crops from oxidative damage caused by waterlogging but it is also untested in broad scale agriculture (Savvides et al., 2016; Andrade et al., 2018). Use of tolerant species and varieties is the cost-effective option for smallholder’s farmers (Tewari and Mishra, 2018; Wani et al., 2018).

However, the introduction of waterlogging tolerance into a crop is time consuming and complex. This trait is controlled by many different mechanisms, such as aerenchyma formation in roots (Luan et al., 2018; Pujol and Wissuwa, 2018) under waterlogging stress, tolerance to secondary metabolites (Pang et al., 2006), ion toxicities (Huang et al., 2018), the maintenance of membrane potential (Gill et al., 2018) and control of reactive oxygen production under stress, with many quantitative trait being reported to control these traits (Huang et al., 2018; Gill et al., 2018).

1.2.6. Crop models used in simulating water dynamic and flood effects in cropping system

As available tools for assessing the potential impacts of climate variability and change on cropping systems, for predicting yield under different constrains and to test the efficiency of crop management options from field to regional scales, crop simulations models, first developed for well drained agricultural soils under semi-arid environments, are currently tested to increase their performance under excessive soil moisture due to water table or excessive rainfall (Jones et al., 2016; Doro et al., 2017; Ebrahimi-Mollabashi et al., 2019). Worou et al. (2012) pointed out slightly delay in the occurrence of a ponded water table in excessive soil moisture conditions and the absence of continuous subsurface flow consideration between areas with different elevation across the landscape by a one-dimensional crop model. Coupled with hydrologic model, crop growth models performance has been improved on the simulation of the groundwater table positive and negative effects on crop (Zhou et al., 2012; Han et al., 2015), but they were still performed better under water limited conditions than excessive water conditions (Warren et al., 2015; Shaw and Meyer, 2015). Indeed, in the mechanistic crop simulation models algorithms, a calculated dynamic aeration stress factor can reduce the potential biomass production (EPIC model; Williams, 1995), increase the potential transpiration (Aquacrop model; Steduto et al., 2009); reduce photosynthesis in Agricultural Production Systems sIMulator model for sugarcane "APSIM sugarcane") (Keating et al., 1999), and/or can slacken the root growth (CERES-maize; Rosenzweig et al., 2002), APSIM-wheat (Asseng et al., 1997). In addition, to different aeration stress approaches among the crop models, aeration stress algorithms differs among the crop models (Jones et al., 1991; Asseng et al., 1997; Calmon et al., 1999; Skaggs, 2008; Qian et al., 2017) and in most cases, the lack of experimental data force to adjust the critical aeration factor included in crop models because it provided simulations which failed within the range of observed values in experimental studies affected by waterlogging (Gaiser et al., 2010; Yamauchi et al., 2018). Some crop simulation models (SWAGMAN Destiny; Meyer et al., 1996), DRAINMOD (Skaggs, 2008) and APSIM (Asseng et al., 1997) built on empirical approaches including reduction in crop yield as a function of number of days with water table on 30 cm soil depth, seems to account for excessive moisture impacts on crop (Evans et al., 1991, Shaw et al., 2013). Nevertheless, theirs crop component are weak and their performance are evaluated on their ability to predict subsurface drainage, surface runoff, or water table depths with field measurements.

1.3. Scoping statement and research question

With the increasing frequency of heavy rain events, excessive water and soil waterlogging may potentially be harmful to certain cereal considered as the most important staple crops, critical to food security in the West African Sahel region. Maize (*Zea mays L.*) is grown primarily for food and accounts for 20% of the calorie intake of 50% of the population (Smale et al., 2013).

It has no naturally occurring air spaces in their roots. Therefore, from a gradual decline in oxygen, its roots suffer from hypoxia (low oxygen) followed by anoxia (no oxygen), when it is exposed to prolonged soil moisture exceeding 80% of the field capacity (Dennis et al., 2000; Zaidi et al., 2003). Limited work has been done on the sensitivity of the West African maize cultivars to soil waterlogging (Otie et al., 2019). Most of the previous conclusions were drawn from experiments conducted in pots (Jaiswal and Srivastava, 2015; Yang et al., 2016; Wang et al., 2017; Li et al., 2018; Kaur et al., 2019; Panozzo et al., 2019; Otie et al., 2019), in lysimeters or greenhouse enclosures (Duthion, 1982; Lizaso and Ritchie, 1997; Zugui et al., 2013; Ahmad and Kanwar, 1991). Very few experiments were conducted under on farm ambient conditions like those conducted in Asia or Australia (Ren et al., 2016; Ren et al., 2018; Tian et al., 2019).

Knowing that under excessive soil moisture conditions, the rate of loss per growth stages depends on the maize cultivar and the crop management system used (Mtongori et al., 2015), how can we forecast loss and damage induced by excess water stress on staple cereal crops? To answer this question, we hypothesized that maize will response to triggered waterlogging under ambient conditions . The empirical assessments were based on data from a 2-year field trials of controlled and uncontrolled waterlogging on two maize cultivar (*Obatampa*, *Wang-data*) commonly used in the West African Sahel. Hence, we exploited the results to develop an analytical index, trained and tested the Environmental Policy Integrated Climate (EPIC) model for simulation. The objectives of this investigation are described in the next section. The results of this assesment are useful inputs to suppport index-based insurance schemes in the West African Sahel.

1.4. Objectives

The main objective of this research is to delve into practical and analytical methods (e.g. experimental trials, statistical indices, crop model tests, etc.) that can boost index-based crop insurance schemes to account for losses and damages due to soil waterlogging and water stagnation in ambient on-farm environmental conditions.

During two rainy seasons (2017 & 2018), we monitored the effects of induced excess soil water and water stagnation on maize (*Zea mays L.*) under ambient environmental conditions using supplementary irrigation. The specific objective of this controlled experiment was to estimate the observable effects soil anoxia and hypoxia on per growth stage and productivity of *Obatampa* cultivar considering three interactive factors: i) two above-surface water levels (2-3 cm (T2) and 7-8 cm (T7)), ii) two waterlogging durations (i.e. 1-3 days (D3) and 4-6 days (D6)), and iii) three growth stages (i.e. six-leave stage (V6), tasselling stage (VT), and milky stage (R3)). We also investigated the spatio-temporal effects of soil waterlogging on natural floodplain using with *Wang-data* cultivar. The trials were designed by considering three interactive factors: i) three topography (i.e. Upslope (H), middle slope (M) and downslope (B)), ii) two land management options (i.e. plots surrounded by bund (D) and without bunds), and iii) two sowing dates (i.e. first sowing date (D1) and second sowing date (D2)). The specific objective of this natural flooding trial was to investigate the soil water dynamics and the cumulative effect of soil waterlogging of the growth, development and production of *Wang-data* cultivar.

Weather, soil and vegetative material were sampled (see chapter 2). The collected data from both experiments of the two years are used to derive of an analytical index (i.e. Stress Day Index, SDI) as proxy of maize yield loss under excessive soil moisture. The data was also used to calibrate and test the ability of the EPIC crop model to reproduce the observed losses/damages and its potential to forecast them.

1.5. Thesis Scope

This document is organized into 4 chapters (including the general introduction). Chapter 2 describes the study area, the experimental designs and the EPIC model calibration set-up. The result related to: (i) the response to hypoxia and anoxia at different growth stages under controlled on-field conditions in Burkina Faso; (ii) the spatio-temporal maize growth and productivity under floodplain conditions and (iii) the EPIC model calibration and performance are exposed successively in chapter 3.The results of research work are discussed in chapter 4 before the conclusions and perspectives (chapter 5).

2. Material and Methods

2.1. Experimental designs

2.1.1. Controlled waterlogging treatments

The West African Sahel is the region that stretches from the East of Chad republic to the West Coast of Senegal between latitudes 10^{o}N to 20^{o}N, covering thereby the whole country of Burkina Faso and northern Ghana. The rainy season of this region is dominated by the West African monsoon which is confined between May to October with June to September explaining the most important amount of the seasonal rainfall (Salack et al., 2016). Our investigations on the effects of temporally waterlogging on maize crop, were conducted in Burkina Faso in 2017 and 2018 cropping seasons, at Boassa (12°16'56″N, 1°36'14″W), a suburb of Ouagadougou city, Burkina Faso (Figure 2.1). The experimental site had similar climatic conditions as Ouagadougou with 841.6 mm (in 2017) and 795.4 mm (in 2018) recorded as the total rainfall between May and October. Average temperatures were between 35°C and 37°C but maximum temperatures in the month of May get up to 41.5°C and 43.6°C. The monthly relative humidity varied between 19% and 76% in 2017 and between 19% and 82% in 2018. The total evaporation was lowest in August (157 mm), but reached 322 mm in the month of March 2017.

The soil profiles of the experimental site, were derived from the pits dug on the plots and the soil classes were identified according to the World Reference Base for soil resources classification systems (WRB, 2015). The experiment was set-up in June-October, on an imperfectly drained, eutric gleyic fluvisol soil type, deeper than 120 cm (Table 2.1). The first 29 cm layer of soil was a very dark grey soil. At mid-depth (~70 cm), the soil was brown then dark grey at further depths in moist conditions. Yellow-brown oxidation-reduction particles were observed from the median horizon to the end of the soil profile. The texture is silty-sandy in the first layer and sandy-clay in the rest of the profile. The table 2.1 provides further details of the soil profile from surface to 120 cm depth.

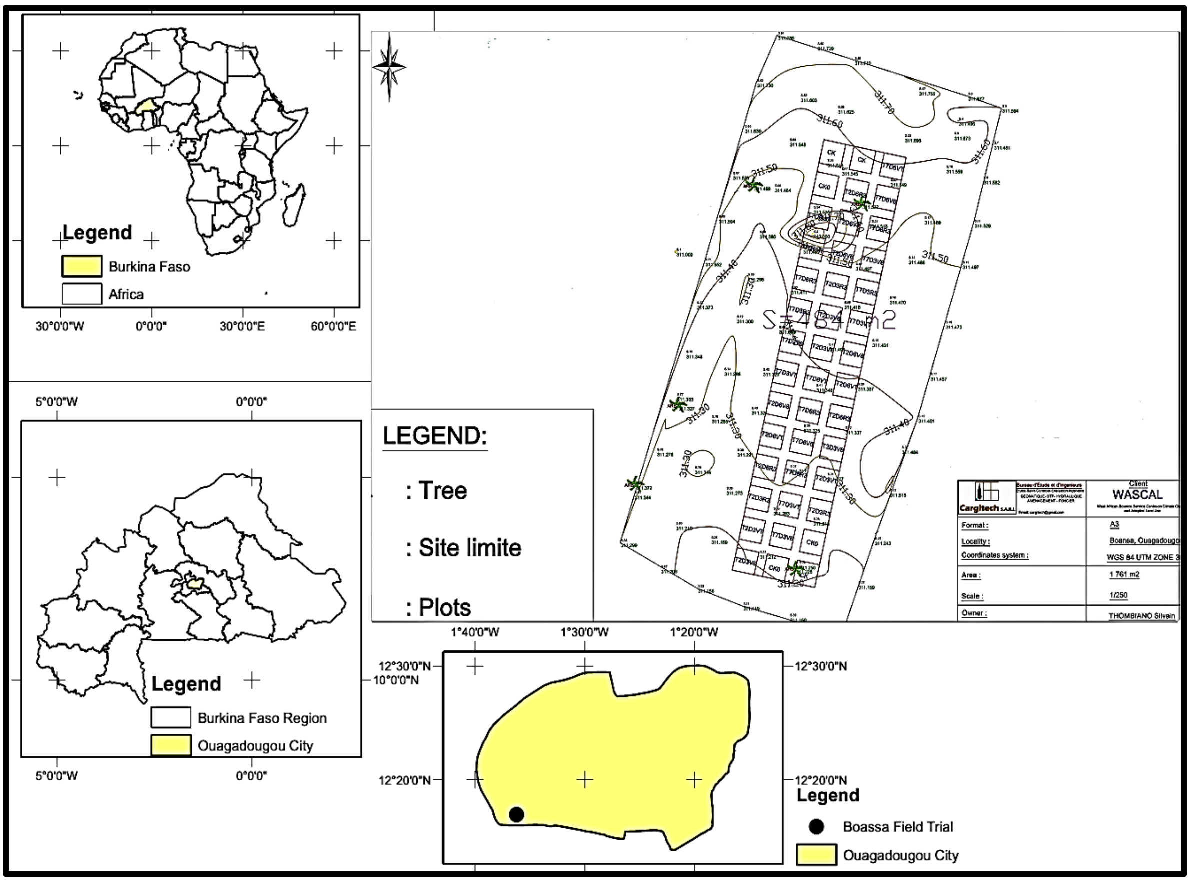


Figure 2.1. Location of the study area and experimental design at Boassa experimental site, Ouagadougou, Burkina Faso.*

* *CK = Control with barriers; CK0 = Control without barriers; T2D3V6 = water level at 2-3 cm applied 3 days at six-leave stage; T2D3VT = water level at 2-3cm applied 3 days at tasselling stage; T2D3R3 = water level at 2-3cm applied 3 days at milky stage; T2D6V6 = water level at 2-3cm applied 6 days at six-leave stage; T2D6VT = water level at 2-3cm applied 6 days at tasselling stage; T2D6R3 = water level at 2-3cm applied 6 days at milky stage; T7D3V6 = water level at 7-8 cm applied 3 days at six-leave stage; T7D3VT= water level at 7-8cm applied 3 days at tasselling stage; T7D3R3 = water level at 7-8cm applied 3 days at milky stage; T7D6V6 = water level at 7-8cm applied 6 days at six-leave stage; T7D6VT = water level at 7-8cm applied 6 days at tasselling stage; T7D6R3 = water level at 7-8cm applied 6 days at milky stage.*

Table 2.1: Physico-chemical properties of fluvisol at Boassa experimental site (2017)

Physico-chemical properties		Soil layer depth		
		0 - 29 cm	29 - 65 cm	65 – 120 cm
Texture		Silty-Sandy	Silty-Sandy - Clay	Sandy-Clay
Clay	%	9.80	27.45	39.22
Silt	%	17.65	19.61	11.76
Sand	%	72.55	52.94	49.02
Moisture at field capacity (pF 2.5)	%	15.74	8.69	13.04
Soil moisture at suction (pF 3.0)	%	11.17	5.78	9.33
Moisture at permanent wilting point (pF 4.2)	%	4.50	2.61	5.52
Total Organic Matter	%	1.38	1.10	0.78
Total Carbon	%	0.80	0.64	0.45
Total Nitrogen	%	0.07	0.06	0.04
Carbon / Nitrogen ratio		11	11	11
Total Phosphorus	mg/kg	0.07	0.06	0.04
Labile Phosphorus	mg/kg	11	11	11
Total Potassium	mg/kg	786	628	524
Labile Potassium	mg/kg	16.09	11.49	8.57
Calcium (Ca++)	mg/kg	1.82	1.41	1.55
Magnesium (Mg++)	mg/kg	0.16	0.09	0.16
Potassium (K++)	mg/kg	0.14	0.09	0.09
Sodium (Na+)	mg/kg	0.05	0.02	0.02
Somme of Bases	mg/kg	2.17	1.61	1.82
Exchangeable Cation Capacity (T)		3.50	2.43	2.65
Saturation rate (S/T)	%	62	66	69
pH $_{H2O}$ (1/2.5)		5.21	5.42	5.66
Vertical saturated conductivity	mmho/cm	0.37	0.14	0.13

In this controlled experiment, we used a split-split plot design with 2 control treatments and 3 replications including: (i) two above-surface water levels (2-3 cm and 7-8 cm), (ii) two waterlogging durations (i.e. 3 days and 6 days), and (iii) three growth stages (i.e. six-leave or jointing stage (V6), tasselling stage (VT), milky stage (R3) of the *Obatampa* maize cultivar. The experimental design is illustrated by figure 2.2.

In order to cause water stagnation and avoid lateral water advection during the waterlogging periods, a black plastic tarpaulin of 7 microns was buried from the surface up to 70 cm depth, combined with 20 cm height bunds (Figure 2.2a). The plots were separated by 100 cm inter-plot spacing (figure 2.2b, 2.2c) and manual ploughing was used to construct the bunds. There were two non-flooded controls (i.e. a control plot with plastic tarpaulin barrier (CK) and an absolute control without plastic tarpaulin barrier (CK0). Each replication contained 14 sub-plots of 6.76 m^2 for the treatments.

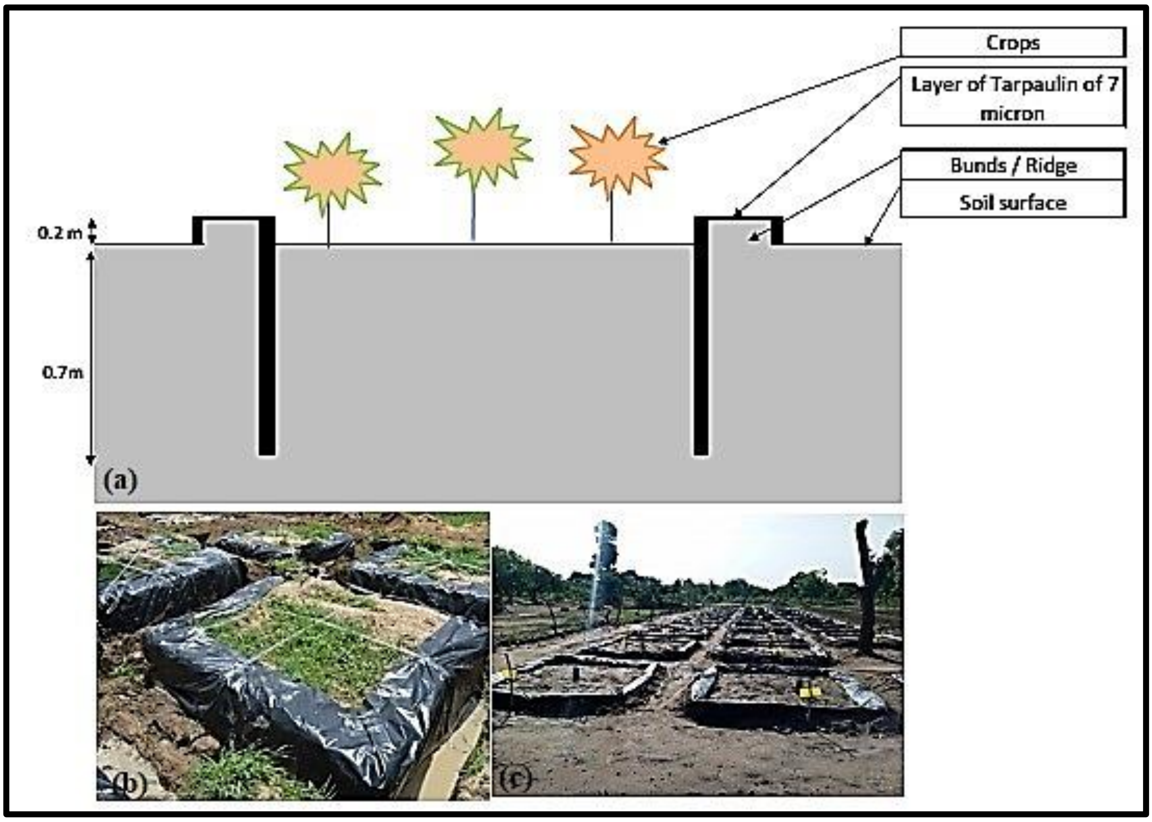


Figure 2.2 Set-up of plots units for Boassa experiment in 2017 and 2018 (a). Upper view of the plot unit (b) and plots layout (c).

Weather variables were collected using an automatic weather station installed on-site. They include solar radiation, maximum and minimum temperature, relative humidity, wind speed and rainfall. The volume of complementary irrigation water was recorded alongside the daily water level in the 30 cm topsoil. The water level data collected through “pani pipes” installed at the center of each plot, were used for the analytical framework following the recommendations by Prithwiraj (2017).

Crop management practices were recorded for each calendar of the cropping season (Table 2.2). Thirty days after sowing (DAS), vegetative material was sampled every 15 days from a set of 5 randomly selected plants. This vegetative material is used to observe some crop growth and development parameters (plant height, leaf length and width, leaves number, tasselling, flowering, silking and physiological maturity), and to derive others variables such as the leaf area index (LAI). To deduct the weight of dry matter, above ground biomass was collected 48 DAS, 68 DAS and at the harvest and dried in an oven at 70°C for 72 hours in both 2017 and 2018. At physiological maturity, ears on plots were completely harvested on each plot, weighted after 10-day sun drying in order to determine grain yield.

Table 2.2: Cropping calendar and crop management practices during 2017 and 2018 at Boassa experimental site

Crop management	Dates	Dosage
Tarpaulin placement	22th June 2017 / 30th May 2018	-
Bunding	06th July 2017 / 25th June 2018	-
Manual ploughing	06th July 2017 / 27th June 2018	-
Sowing	08th July 2017 / 17th July 2018	62500 seeds ha^{-1}
First manual weeding	17th July 2017 / 29th August 2018	-
First fertilization	26th July 2017 / 08th August 2018	625 kg ha^{-1} of NPK 23-10-5
Second manual weeding	3rd August 2017 / 07th September 2018	-
Waterlogging treatments at vegetative stage	11th August 2017 / 18th August	-
First pest control	15th August 2017	6 ml ha^{-1} PYRINEX QUICK 212 EC
	29th August 2018	21.13 g ha^{-1} EMACOT 50WG
Third manual weeding	22th August 2017 / 30th September 2018	-
Second fertilization	27th August 2017 / 07th September 2018	62.5 kg ha^{-1} of Urea (46 % N) 375 kg ha^{-1} of Ammonium sulfate (21 % N)
Waterlogging treatments at tasselling	30th August 2017 / 8th September 2018	-
Second pest control	6th September 2017	8 ml ha^{-1} PYRINEX QUICK 212 EC
	1st September 2018	21.13 g ha^{-1} EMACOT 50WG
Fourth manual weeding	25th September 2017	-
Third pest control	25th September 2017	12 ml ha^{-1} PYRINEX QUICK 212 EC
Waterlogging treatments at grain filling stage	29th September 2017 / 25th September 2018	
Pest treatment	30th September 2017	12 ml ha^{-1} PYRINEX QUICK 212 EC
Harvest	14th October 2017 / 20th October 2018	-

2.1.2. Natural flooding trials

For the effect of uncontrolled waterlogging on maize, the trials were located at Aniabisi, in Bolgatanga municipality, in the north-eastern region of Ghana (Figure 2.3). The site has an annual rainfall ranging from 756 to 1000 mm. Average annual temperatures vary between 28 °C and 39 °C. The soils at Aniabisi were characterized in 2012 to a depth of 60 cm are mainly plinthosols (top of slope) and luvisols (low slope or low altitude zone) (Danso, 2015).

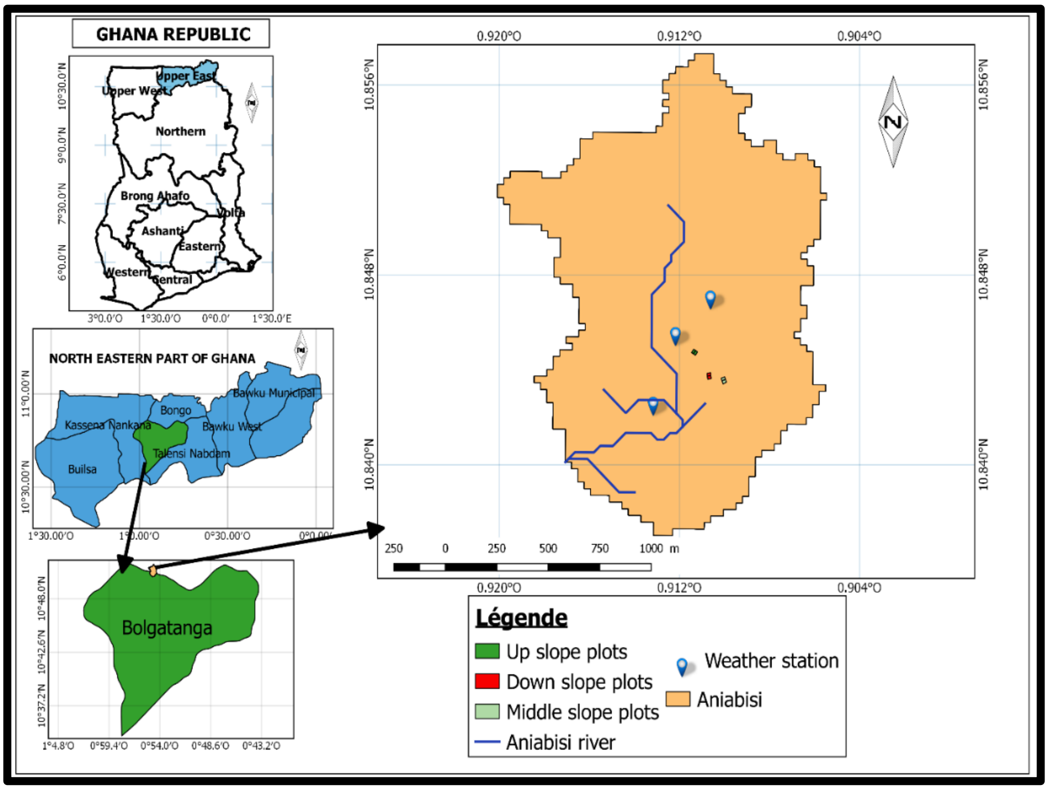


Figure 2.3. Location of the study area and experimental plots at Aniabisi experimental site, Bolgatanga, Ghana

The uncontrolled waterlogging treatment was set up, following a split-split-plot design with 3 repetitions: i) three topographic positions as a main factor of the main plots (upslope, middle slope, and downslope); ii) two types of water management practices as a factor at the plot level (the presence or absence of bunds which affect the natural water flow) and iii) two sowing dates (first and second sowing date). Indeed, the main bloc located up, middle and down slopes with respect to the stream (Figure 2.4). Those blocs contain two plots (one surrounded with sand bunds of 0.3 m of height and the second without bunds). Each plot had 6 subplots (5m × 6m), where two sowing dates were repeated 3 times. Finally, 12 treatments were repeated 3 times, and were randomly distributed into 36 subplots.

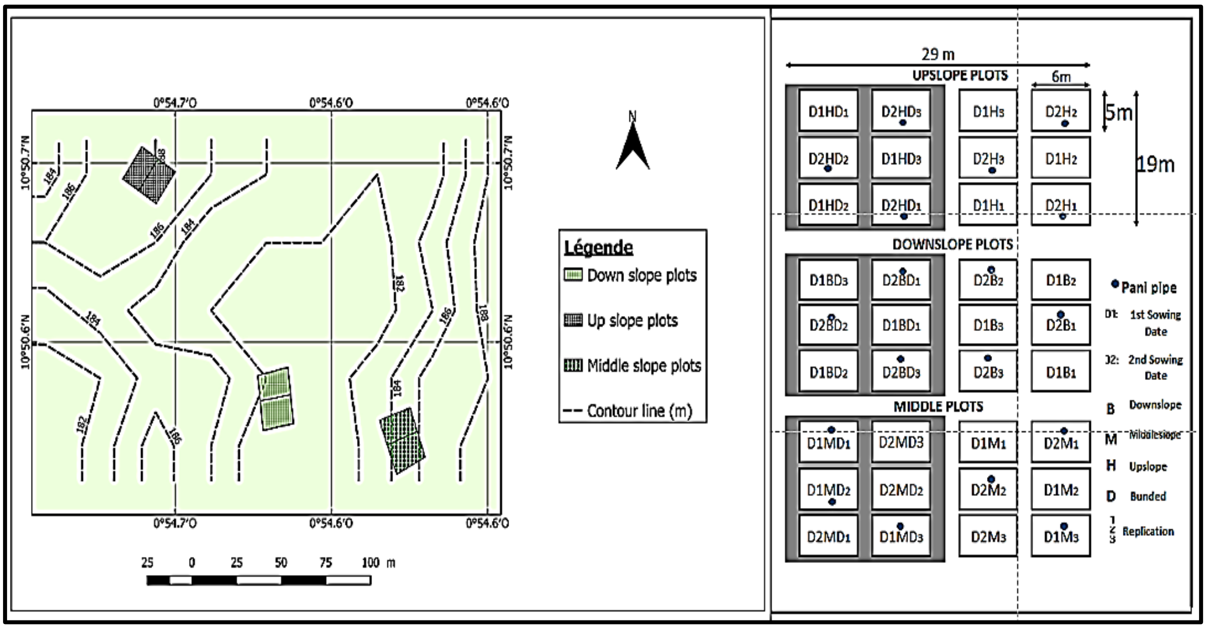


Figure 2.4. Experimental set-up of Aniabisi trials in 2017 and 2018 (Bolgatanga, Ghana)[*].

[*]*D1HD1 : First sowing date at upslope on bunded subplot replication 1 ; D1HD2 : First sowing date at upslope on bunded subplot replication 2 ; D1HD3 : First sowing date at upslope on bunded subplot replication 3 ; D1H1 : First sowing date at upslope on unbunded subplot replication 1 ; D1H2 : First sowing date at upslope on unbunded subplot replication 2 ; D1H3 : First sowing date at upslope on unbunded subplot replication 3 ; D2HD1 : Second sowing date at upslope on bunded subplot replication 1 ; D2HD2 : Second sowing date at upslope on bunded subplot replication 2 ; D2HD3 : Second sowing date at upslope on bunded subplot replication 3 ; D2H1 : Second sowing date at upslope on unbunded subplot replication 1 ; D2H2 : Second sowing date at upslope on unbunded subplot replication 2 ; D2H3 : Second sowing date at upslope on unbunded subplot replication 3 ; D1MD1 : First sowing date at middle-slope on bunded subplot replication 1 ; D1MD2 : First sowing date at middle-slope on bunded subplot replication 2 ; D1MD3 : First sowing date at middle-slope on bunded subplot replication 3 ; D1M1 : First sowing date at middle-slope on unbunded subplot replication 1 ; D1M2 : First sowing date at middle-slope on unbunded subplot replication 2 ; D1M3 : First sowing date at middle-slope on unbunded subplot replication 3 ; D2MD1 : Second sowing date at middle-slope on bunded subplot replication 1 ; D2MD2 : Second sowing date at middle-slope on bunded subplot replication 2 ; D2MD3 : Second sowing date at middle-slope on bunded subplot replication 3 ; D2M1 : Second sowing date at middle-slope on unbunded subplot replication 1 ; D2M2 : Second sowing date at middle-slope on unbunded subplot replication 2 ; D2M3 : Second sowing date at middle-slope on unbunded subplot replication 3 ; D1BD1 : First sowing date at downslope on bunded subplot replication 1 ; D1BD2 : First sowing date at downslope on bunded subplot replication 2 ; D1BD3 : First sowing date at downslope on bunded subplot replication 3 ; D1B1 : First sowing date at downslope on unbunded subplot replication 1 ; D1B2 : First sowing date at downslope on unbunded subplot replication 2 ; D1B3 : First sowing date at downslope on unbunded subplot replication 3 ; D2BD1 : Second sowing date at downslope on bunded subplot replication 1 ; D2BD2 : Second sowing date at downslope on bunded subplot replication 2 ; D2BD3 : Second sowing date at downslope on bunded subplot replication 3 ; D2B1 : Second sowing date at downslope on unbunded subplot replication 1 ; D2B2 : Second sowing date at downslope on unbunded subplot replication 2 ; D2B3 : Second sowing date at downslope on bunded subplot replication 3.*

Plant spacing was 0.75 m × 0.40 m following the suggestion by VOTO (2015) with the plant density of 66.67 plants/ha. Pest attacks, particularly fall-army worm (*Spodoptera frugiperda*), were controlled by using PYRINEXQUICK 424EC (Deltamethrin, 24 g/l + chloropyriphos-ethylic (400 g/l) and EMASTAR (Emamectin benzoate, 20 g/l + Acetamiprid, 64 g/l).

Mineral fertilizers, NPK (23-10-5), urea (46% N) and ammonium sulphate (21% N) were applied to the maize cultivar named "*Wang-data*". It is a white maize cultivar, resistant to drought and Striga (*Striga hermonthica* (Delile) Benth.), which has been developed in 2012 by the International Institute of Tropical Agriculture (IITA) in collaboration with International Maize and Wheat Improvement Center (CIMMYT) and the Crop Research Institutes of Kumasi and Tamale (CSIR-CRI Kumasi, CSIR-SARI Tamale), to facilitate the resilience of maize producers to drought (Sipalla and Sipalla, 2013). Water level dynamics, was monitored using polyvinyl chloride (PVC) pipes of 0.50 m high perforated on 0.30 cm, called "pani pipes"). The pipes were randomly on the experimental plots.

Alongside crop management practices (Table 2.3), vegetative material sampling and measurements (plant height, leaf length and width, number of leaves, aboveground biomass) were conducted every 15 days, starting from 30 DAS. Leaf area index (LAI) was estimated based on the measurement data (Ren et al., 2014). The aboveground biomass at 30 DAS, 60 DAS and 90 DAS was estimated by sampling plants over a 1 m × 1 m subplot. At maturity (R6), plot ears were fully harvested on each plot to estimate grain yield. Post-harvest spikes were sun-dried over 10 days after the harvest.

Table 2.3: Cropping calendar and crop management practices during 2017 and 2018 at Aniabisi experimental site

Crop management	Dates	Characteristics
Construction of bunds	16th June 2017/19th May 2018	30 cm of height
Manual ploughing	17th June 2017/19th May 2018	Depth 10 cm
First date sowing	19th June 2017/31st May 2018	66 667 plants.ha^{-1}
Second date sowing	3rd July 2017/21th June 2018	
Thinning for the first date planting	3rd July 2017/13th June 2018	Thinning at 2 plants par hole
Thinning for the second date planting	17th July 2017/7th July 2018	Thinning at 2 plants par hole
First fertiliser application for the first date planting	7th July 2017/20th June 2018	333.335 kg.ha^{-1} of NPK 23-10-5
Second fertiliser application for the first date planting	24th July 2017/10th July 2018	333.335 kg.ha^{-1} of NPK 23-10-5
Third fertiliser application for the first date planting	07th August 2017/27th August 2018	400.002 kg.ha^{-1} of Aluminium silicate (21 % N)
First fertiliser application for the second date planting	24th July 2017/10th July 2018	333.335 kg.ha^{-1} de NPK 23-10-5
Second fertiliser application for the second date planting	07th August 2017 / 20th July 2018	333.335 kg.ha^{-1} de NPK 23-10-5
Third fertiliser application for the second date planting	20th August 2017/ 07th August 2018	400.002 kg.ha^{-1} of Aluminium silicate (21 % N)
Manual weeding 1	3rd July 2017/17th June 2018	
Manual weeding 2	12th July 2017 / 06th July 2018	
Manual weeding 3	1st August 2017/ 27th July 2018	
Manual weeding 4	26th August 2017 / -	
Chemical weeding 1	15th July 2017 /	KABAHERB applied at 720mg / l
Pest control 1	15th July 2017/15th June 2018	PYRINEXQUICK 424 EC applied
Pest control 2	3rd August 2017 / 03rd July 2018	at 0.25 ml/l + 3.125 ml/l of
Pest control 3	16th August 2017 / 30th July 2018	EMASTAR
Pest control 4	16th August 2018	125 ml/l of EMASTAR
Pest control 5	13th August 2018	FORABAT applied at 200kg.ha^{-1}
Harvest of the first planting date	19th September 2017/ 13th September 2018	Manual harvest
Harvest of the second planting date	03th October 2017/ 20th September2018	

2.2. Crop model simulations: The EPIC crop model

2.2.1. General Description

The Environmental Policy Integrated Climate (EPIC) is a mechanistic crop simulation model, originally built in the year 1980s, to quantify the effect of wind or water erosion on crop productivity (Williams et al., 1984; Jones et al., 1991). It has evolved into a comprehensive agro-ecosystem model capable of simulating crops growth and productivity under various cropping systems (Williams, 1995). It can potentially account for relevant processes that may occurs in extreme rainfall and soil waterlogging conditions :soil water content and water table depth dynamics, nutrients as such as nitrogen, phosphorous and potassium deficiencies, soil salinity, aluminium toxicity, oxygen deficiency, soil erosion (Van der Velde et al., 2011). Operating on a daily step, the essential modules of EPIC are: (i) crop growth; (ii) weather generator; (iii) soil water dynamics and hydrology; (iii) soil temperature; (iv) soil erosion by wind and water; (v) tillage; (vi) nutrient (N, P, K) and carbon cycling and crop and soil management (Williams, 1995). There is also cost-benefit calculator integrated in the model which can potentially be used for economic assessment of losses and damages. The Figure 2.5 describes the conceptual framework of the EPIC model.

In the EPIC model, different potential evapotranspiration (PET) equations are available for reasonably simulating yields. Different management options including tillage, irrigation, fertilizer application rates and timing are also available. Potential biomass is calculated on daily basis, from photo-synthetically active radiation and radiation-use efficiency. Daily gains in plant biomass are affected by vapour pressure deficits and atmospheric CO_2 concentration (Stockle et al., 1992a;b). Potential biomass is adjusted to actual biomass through daily stress caused by extreme temperatures, water and nutrient deficiency or inadequate soil aeration. Similarly, stress factors temperature, and aluminium toxicity are used to adjust potential root growth (Jones et al., 1991).

Harvest index is calculated as a ratio of yield over total actual above-ground biomass at maturity. Crop growth is defined by thermal time (PHU), the biomass-energy conversion factor and the harvest index (Wang et al., 2005). The PHU was calculated from the daily temperature as accumulated temperature from sowing to maturity minus the crop base temperature. Yield losses due to nutrient stress are mainly controlled by nutrient supplies through crop management module. Water stress is effectively controlled through soil water balance, which is especially sensitive to the chosen PET method (Roloff et al., 1998), and supplementary irrigation. The critical aeration factor for crop (CAF) and water content of the top 1 m are also account for the estimation of the degree of aeration stress (Williams and Izaurralde, 2009).

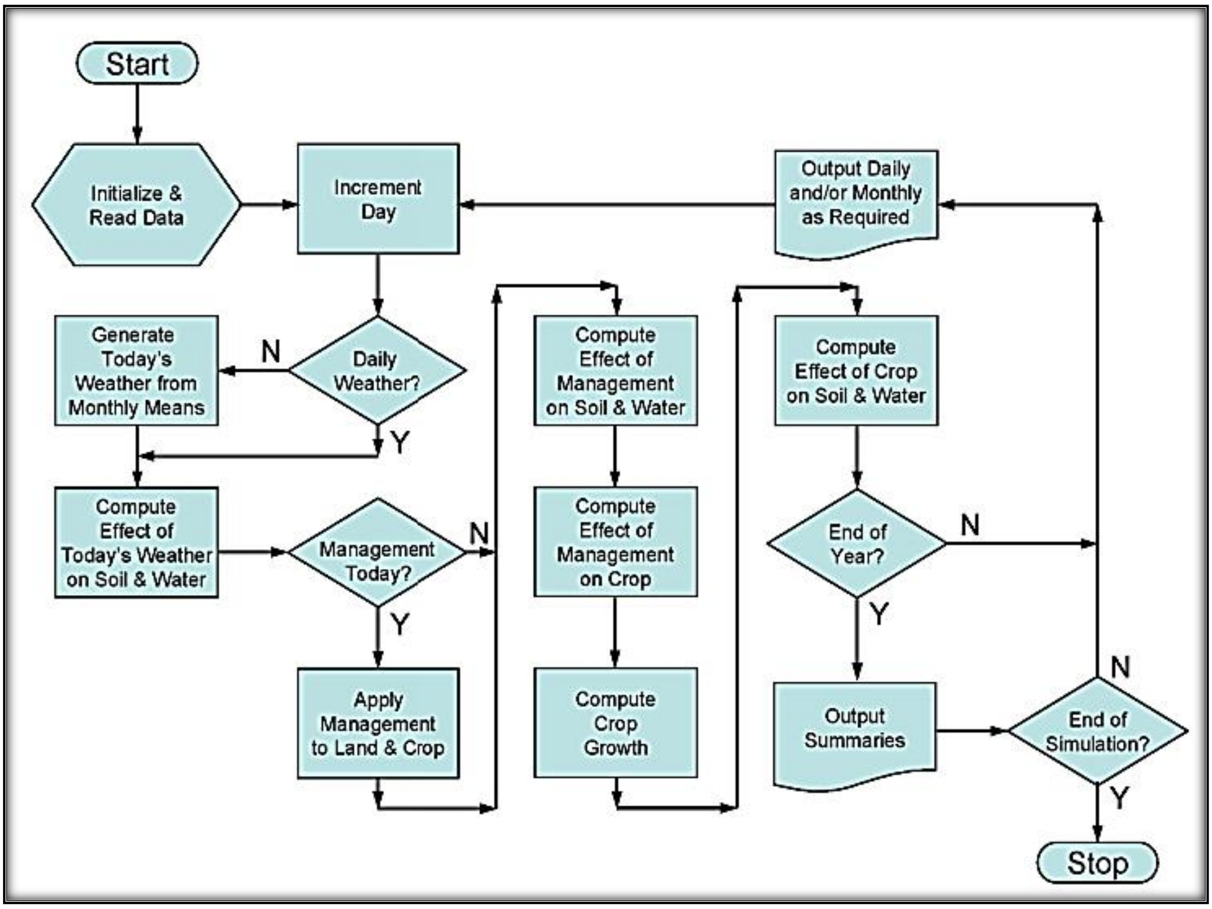


Figure 2.5. EPIC Model flow diagram (Gerik et al., 2015)

The i_EPIC interface (http://www.public.iastate.edu/~tdc/i_epic_main.html) was run under the version 0810. The main data inputs include daily weather data (solar radiation, maximal and minimum temperature, rain, relative humidity, wind speed), initial soils conditions and crop management files. The outputs deemed relevant for our study are data on crop productivity (leaf area index, total aboveground biomass and grain yield) and soil water content. Soil water content dynamics in the model is linked with water movement affected by evapotranspiration, runoff, sub-lateral flow and percolation. The water storage routing technic allows vertical or horizontal flow from a soil layer when soil water content exceeds the field capacity. EPIC executes the soil water movement from the fluctuation in soil water content. Above field capacity, the water loss by percolation increases groundwater recharge. Water drains from the layer with regard to layer storage and saturated conductivity until the storage returns to field capacity (Worou et al., 2012). The user can reasonably adjust the hydraulic conductivity, because of the weakness of tipping-bucket approach, in simulating elevated soil water conditions where soil moisture levels may remain above field capacity under prolonged wet weather periods or limited drainage (Doro et al., 2017).

The crop growth module of EPIC is based on a unique file of crop growth parameters used for all simulations. The main parameters of this file are the: (i) radiation use efficiency (WA) which regulate the conversion of intercepted light into biomass; (ii) potential harvest index (HI); (iii) maximum leaf area index (maximum LAI), (iv) LAI development curve represented by two LAI value at 2 development stages (DPLAP1, DLAP2).

The biomass derived from the intercepted active radiation by the plant canopy which is regulate by the LAI and the radiation use efficiency. Without any stress, it grows according to the cumulated heat units until maximum LAI. Under aeration stress, crop specific critical aeration factor is the fraction of soil porosity where poor aeration starts limiting crop growth if soil water content exceeds this threshold. It can be adjusted in order to well simulate the aeration stress (Gaiser et al., 2010). In term of crop phenology simulation, the crop growth stages are not simulated by the model, but the potential heat unit is used for the determination of crop cycle. Final grain yield is generated from the final biomass with the potential harvest index (HI).

2.2.2. Calibration method of the EPIC model

Boassa datasets (i.e. data from samples of the controlled experiment) were used for calibration and data from Aniabisi trials (i.e. Samples from the upslope and downslope floodplain trials) were used for validation. Daily rainfall, maximum and minimum air temperature, solar radiation, relative humidity and wind speed were used as input to the EPIC model. In 2017, complementary data from the synoptic station of Ouagadougou, sunshine hours were converted to the solar radiation following to the FAO recommendations (FAO, 2009). For validation, weather data from Aniabisi (northern Ghana), were also used to force the EPIC model. The section 2.1 describes the trend observed in rainfall and temperature on the two research sites. The potential evapotranspiration was estimated by the model with the Penman–Monteith method (1965) as described by Williams (1995).

The soil water dynamics and hydrology routines of the model calibrated and validation to capture the experimental waterlogging periods, during 2017/2018. Soil water holding capacity and lateral flows parameters for both the absolute control, control plots and waterlogged plots adopted for Boassa and added water table conditions for Aniabisi are summarized in the table 2.4.

Table 2.4: Soil input parameters used for calibration and validation of soil water dynamics

Site	Treatments	Soil depth (cm)	Water content Field Capacity (m3/m3)	Wilting point (m3/m3)	Saturated conductivity (mm/h)	Lateral hydraulic conductivity (mm/h)
Boassa	Control CK0	0 -29	0.16	0.04	10.73	0.32*
		29 - 65	0.09	0.03	5.04	0.15*
		65 - 120	0.13	0.05	7.15	0.21*
	Control CK	0 -29	0.16	0.04	10.73	0.9**
		29 - 65	0.09	0.03	5.04	0.9**
		65 - 120	0.13	0.05	7.15	0.21*
	Flooded Treatments	0 -29	0.16	0.04	10.73	0.9**
		29 - 65	0.09	0.03	5.04	0.9**
		65 - 120	0.13	0.05	7.15	0.21*
					Minimum / Maximum depth of water table (m)	of water table (m)
Aniabisi	Upslope with or without bunds	0 -20	0.15***	0.04***		
		20 - 40	0.18***	0.08***		
		40 - 60	0.18***	0.08***		
	Downslope with bund	0 -20	0.15***	0.04***	0.30**	0.30**
		20 - 40	0.18***	0.08***		
		40 - 60	0.18***	0.08***		
	Downslope without bund	0 -20	0.15***	0.04***	0.32**	0.32**
		20 - 40	0.18***	0.08***		
		40 - 60	0.18***	0.08***		

**Default values; ** recalibrated values ***Danso(2015)*

The field capacity and wilting point of each layer were determined from laboratory analysis including, the volumetric water content at metric potential pF=2.5 and pF 4.2. (Table 2.1). Modification of lateral hydraulic conductivity in the calibration process was explained by the presence of a black plastic tarpaulin of 7 microns around the control CK0, was buried from the surface up to 70 cm depth. According to Duong et al. (2019), the unsaturated soil hydraulic conductivity (HC) controls the transient seepage, the depth of rainfall infiltration and the changes in pore pressure during the rainfall event. Hence, high hydraulic conductivity leads to rapid soil saturation and infiltration causes the wetting front to quickly shift downward causing a rapid rise in pore-water pressure and the formation of a perched water table.

The PHU of each crop and treatments, was estimated according to daily temperature fluctuation and growth cycle duration. Then, due to daily temperature fluctuation and cropping cycle duration of each tested treatment, the value varied from 1250°C – 1634°C.

For *Obatampa* and *Wang-data* cultivars, the average PHU were 1634°C and 1250°C respectively. The Heat Units required for Germination (GMHU) was changed into 113.6 according to the observed date of emergence and the thermal time (PHU) between date of sowing and 50% of emergence.

Obatampa cultivar is an improved maize cultivar which has with higher value of LAI (Fosu-Mensah, 2012). Leaf area development curve depend of two points collected under optimal conditions with special nomenclature (DLAP1 and DLAP2 with numbers before decimal are % of growing season. Numbers after decimal are fractions of maximum potential LAI). For *Obatampa* cultivar, the DLAP1 and DLAP2 were changed into 40.50 and 45.92. The field data reveal that 50% flowering stage were reached around 52 DAS and the maturity date were around 107 DAS, considering all treatments. The potential biomass growth depends on the biomass-energy ratio.

When soil moisture approaches saturation (SAT), maize suffered from aeration stress. In EPIC model, the soil moisture on 1 m of soil depth is considered in the estimation of aeration stress (AS) according the following algorithms (Williams and Izaurralde, 2009):

$$SAT = 100 \times \frac{\frac{ST_1}{PO_1} - CAF_{(i)}}{1 - CAF_{(i)}} \qquad (1)$$

where ,

SAT is the saturation factor

ST_1 is the water content minus field capacity of the top 1 m of soil in mm

PO_1 is the porosity minus field capacity of the top 1 m of soil in mm

and $CAF_{(i)}$ is a critical aeration factor for crop i

$$AS_{(i)} = 1 - \frac{SAT}{\text{SAT} + e^{(2.901 - 0.0387 * \text{SAT})}} \quad if\ SAT > 0 \qquad (2)$$

$$where\ AS_{(i)}\ is\ the\ aeration\ stress\ factor\ for\ crop\ i$$

$$AS_{(i)} = 1\ \ if\ SAT < 0 \qquad (3)$$

These AS stress vary between 0 and 1 and more it's close to 0, more it constraints biomass accumulation, root growth, and yield. Changes in the critical aeration factor (CAF) were necessary because of the induced waterlogging and the observation through the "pani pipe" of natural soil waterlogging of sites. More calibrated parameter is provided in table 2.5.

The calibration was restricted to the improvement of the goodness of induced waterlogging period and also the accuracy of fitness between observed and simulations by adjusting model parameters input variables to which simulated growth, development and production are most sensitive to. However, the source code of the model remained unchanged. For model validation, an independent data set from two-year experiment on uncontrolled effects of waterlogging (see section 2.1.2).

Table 2.5: Parameter setting for maize in the EPIC crop file: original defaults and values after calibration and validation

	WA	TB	HI	PPL1	PPL2	LAIMX	BN2	BN3	PPC1	PPC2	CAF	GMHU	PHU
Original	40	25	0.5	4/15.05	7/50.95	6	0.016	0.013	15.05	50.95	0.855	100	1500
Obatampa	43	29.75	0.47	1/40.5	8/45.92	6	0.008	0.0065	40.5	45.92	0.45	113.5	1634
Wang data	30	25	0.57	1/40.5	8/55.92	3.5	0.008	0.0065	40.5	55.92	0.45	113.5	1250

(WA, biomass-energy conversion factor; TB, optimal temperature; HI, potential harvest index; LAIMX, maximum leaf area index; PPL1/PPL2, plant density - LAI parameters; CAF, critical aeration factor; PHU, potential heat unit; GMHU , germination heat unit)

2.2.3. Analysis of losses, damages and EPIC crop model performance assessments

All datasets collected from the samples on both the controlled and uncontrolled trial were subjected to an analysis of variance and statistical significance tests using a pulled-variance Student *t*-test for the normally distributed samples and a Kruskal Wallis test (McKight and Najab, 2010) for the samples which were not normally distributed, at 95% confidence interval.

During the trials, the volume of complementary irrigation water was recorded alongside the daily water level in the 30 cm topsoil. The water level data collected through “pani pipes” installed at the center of each plot, were used to estimate the excess water stress-day factor (SEW30), (Kanwar et al., 1998) and the Stress Day Index (SDI) (Ravelo et al., 1982; Hardjoamidjojo et al., 1982; Kanwar, 1988; Shaw and Meyer, 2015) following equations 1 and 2:

$$SEW30 = \sum_{i}^{n}(30 - WTD_i) \qquad (4)$$

where n is the number of days and WTDi is the daily water table depth (cm) in the 30 cm topsoil.

Water-level hydrographs were drawn on daily basis using the water table data collected from each pani pipe per plot. The water table depth data for the days when water-table is above the soil surface is considered to be null in the SEW30 estimation. SEW30 values quantify the excessive soil water conditions in cm.day unit.

$$SDI = \sum_{j}^{m}(CS_J \times SEW30_J) \qquad (5)$$

where *m* is the number of growth stages, CS_j values is normalized crop susceptibility factor for stage *j*, and $SEW30_j$ is a stress-day factor for stage *j*. The table 2.6 provides the normalized crop susceptibility factors for each stage. The stress-day index (SDI) concept quantifies the cumulative stress of wetness on maize during the growing season in cm.day unit.

Table 2.6: Normalized crop susceptibility factors for maize for excessive soil water conditions (adapted from Evans and Skaggs, 1984; Kanwar, 1998)

Growth stage	Days after planting	Normalized mean susceptibility factors (0-1)
Establishment	18	0.16
Early vegetative	36	0.18
Late vegetative	56	0.38
Flowering	76	0.21
Yield formation	100	0.06

Crop management practices were recorded for each calendar of the cropping season. Vegetative material is sampled every 15 days from a set of 5 randomly selected plants starting from Thirty days after sowing (DAS), This vegetative material is used to observe some crop growth and development parameters (i.e. plant height, leaf length and width, leaves number, tasselling, flowering, silking and physiological maturity), and to derive others variables as such as the leaf area index (LAI). To deduct the weight of dry matter, above ground biomass was collected 48 DAS, 68 DAS and at the harvest and dried in an oven at 70^{o} C for 72 hours in both 2017 and 2018. At physiological maturity, ears on plots were completely harvested on each plot, weighted after 10-day sun drying in order to determine grain yield. The weight of the grain yield per treatment was used to estimate the Relative Yield Loss (RYL) of each treatment:

$$RYL = 100 \times \frac{Y_{TR} - Y_{CK}}{Y_{CK}} \qquad (6)$$

Where Y_{CK} is the dry grain yield from the control plots with barriers (CK) and Y_{TR} the dry grain yield of each treatment.

Model evaluation was based on:

- the coefficient of determination R^2
- mean relative error (MRE)

$$MRE = \frac{1}{n} \sum_{i=1}^{n} \frac{(y_i - x_i)}{x_i} \qquad (7)$$

- root mean square error

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (y_i - x_i)^2\right]^{0.5} \times \frac{100}{\bar{x}} \qquad (8)$$

Simulated stress day index (SSDI) and simulated excessive water stress factor (SSEW) respectively based on the concepts of stress day index (SDI) and excess water stress day factor and including the simulated soil moisture by the model, were tested as yield loss predictor :

$$SSEW = \sum_{i=1}^{n} (SAT - SW29) \qquad (9)$$

$$SSDI = \sum_{i=1}^{n} Cs * (SAT - SW29) \text{ with } SW29 > FC \text{ and } SW29 = SAT \text{ if } SW29 > SAT \qquad (10)$$

Where *W29* = Simulated Soil Moisture in the topsoil layer of 29cm depth; *SAT* = simulated saturation point in the topsoil layer of 29cm depth; *FC* = simulated field capacity in the topsoil layer of 29cm depth; *SAT* = simulated saturation point of the topsoil layer of 29cm depth; *Cs*= maize crop susceptibility to waterlogging (Kanwar et al., 1988). The unit of simulated stress-day index (SSDI) and simulated excessive water stress factor (SSEW) is $m^3.m^{-3}$.day.

3. Results

3.1. Maize response to hypoxia and anoxia at different growth stages under controlled field conditions

This section describes the results obtained from the controlled waterlogging trials and summarizes them in a short concluding and remarks. The results are detailed according to the: (i) soil water level dynamics and excessive water stress; (ii) effects of waterlogging on maize height, leaf area index and flowering; (iii) effects on aboveground biomass and grain productivity and (iv) analytical estimation of loss.

3.1.1. Dynamics of soil water level and excess water stress

During the controlled waterlogging trials, a total volume of 67 mm was applied as complementary irrigation during dry spells events, in order to avoid any water deficit for the plants. On the average, flooding up to 2-3 cm and 7-8 cm above the soil surface were induced using 145.5 mm/day and 210.3 mm/day (at V6 stage), 139 mm/day and 175.6 mm/day (at VT stage) and 156.3 mm/day to 176.3 mm/day (at R3 stage). The excess water induced different water level dynamics per treatment (Figure 3.1). According to the water level depth fluctuating with rainfall and irrigation, the natural soil waterlogging was highly dependent of the altitude where plots were located in the field. Indeed, water level dynamics in the 30 cm depth of the control plots has shown a high exposure of plots located downhill with 9.5% more chance to observe water level in this topsoil layer compared to 3.5% observed on plots uphill (Figure 3.1).

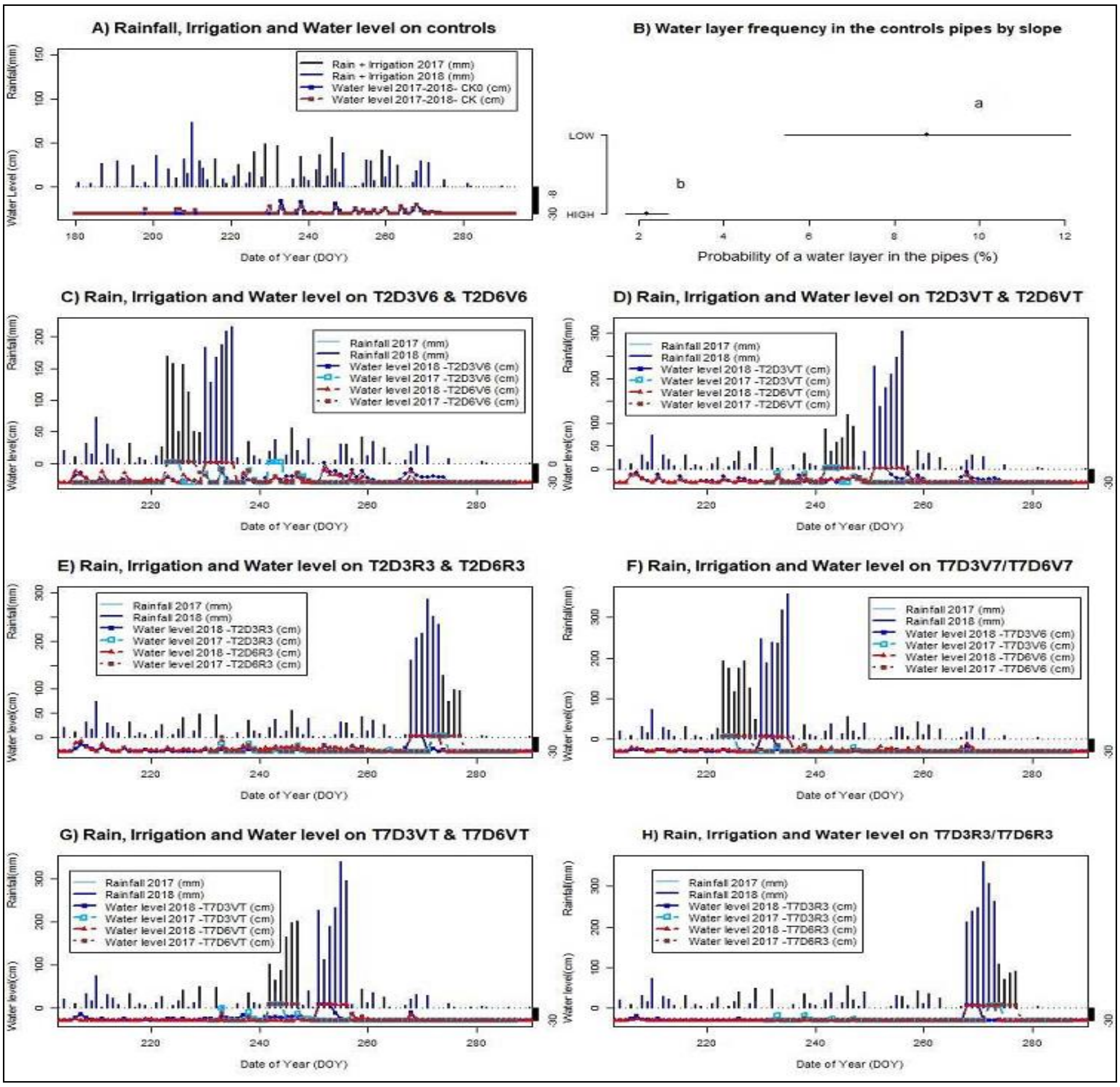


Figure 3.1. Rain, irrigation, water level dynamic (A) and its repartition by slope during 2017 and 2018 on controls (B); Rain, irrigation, water level dynamic on plots flooded at 2-3cm above the soil surface during 3 and 6 days at six-leave stage (C), on plots flooded at 2-3cm above the soil surface during 3 and 6 days at tasselling stage (D), on plots flooded at 2-3cm above the soil during 3 and 6 days at milky stage (E), Rain, irrigation, water level dynamic on plots flooded at 7-8cm above the soil surface during 3 and 6 days at six-leave stage (F), on plots flooded at 7-8cm above the soil surface during 3 and 6 days at tasselling stage (G), on plots flooded at 7-8cm above the soil during 3 and 6 days at milky stage (H)

CK = Control with barriers; CK0 = Control without barriers; T2D3V6 = water level at 2-3 cm applied 3 days at V6 stage; T2D3VT = water level at 2-3cm applied 3 days at VT stage; T2D3R3 = water level at 2-3cm applied 3 days at R3 stage; T2D6V6 = water level at 2-3cm applied 6 days at V6 stage; T2D6VT = water level at 2-3cm applied 6 days at VT stage; T2D6R3 = water level at 2-3cm applied 6 days at R3 stage; T7D3V6 = water level at 7-8 cm applied 3 days at V6 stage; T7D3VT= water level at 7-8cm applied 3 days at VT stage; T7D3R3 = water level at 7-8cm applied 3 days at R3 stage; T7D6V6 = water level at 7-8cm applied 6 days at V6 stage; T7D6VT = water level at 7-8cm applied 6 days at VT stage; T7D6R3 = water level at 7-8cm applied 6 days at R3 stage.

The bunds combined with plastic tarpaulin had no significant effects on the exposure of the control plots (CK and CK0) to waterlogging. Although, bunds can amplify the risk of excess soil water stress but their effect depends on the field topography.

In the top 30 cm depth, the daily water level fluctuations converted into excess water stress-day factor (SEW30) and stress day index (SDI) showed no significant effects on the distribution of the replications (Figure 3.2).

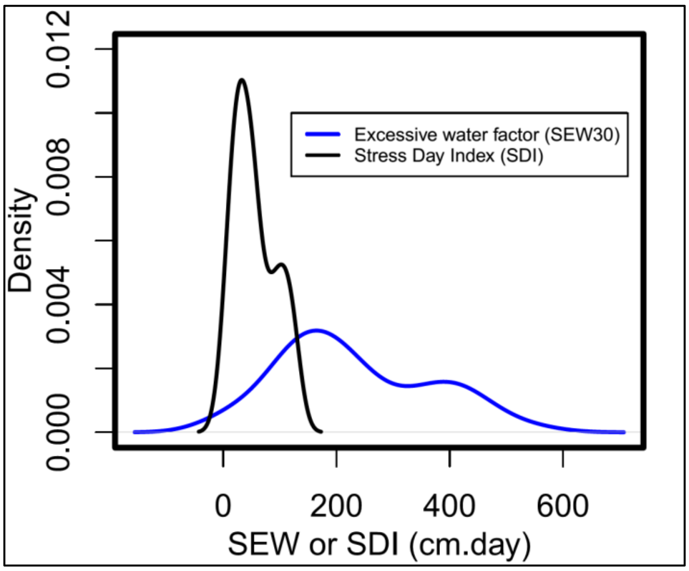


Figure 3.2. Excess water stress indices (SEW30 and SDI) distribution

However, SEW30 increased significantly, when the plots were flooded at VT (274 cm.day/368.2 cm.day) and V6 stages (272.4 cm.day/366.7 cm.day), compared to the control plots (89.3 cm.day/88 cm.day) in 2017/2018. With the increase in the duration of water stagnation, SEW30 and SDI of 6 days flooded plots were significantly higher than the control plots. As a result of position of the plots, SEW30 and SDI increased significantly in the case of 2cm-above-surface flooding (downhill) compared to 7cm-above-surface the soil surface (uphill) (Figure 3.3).

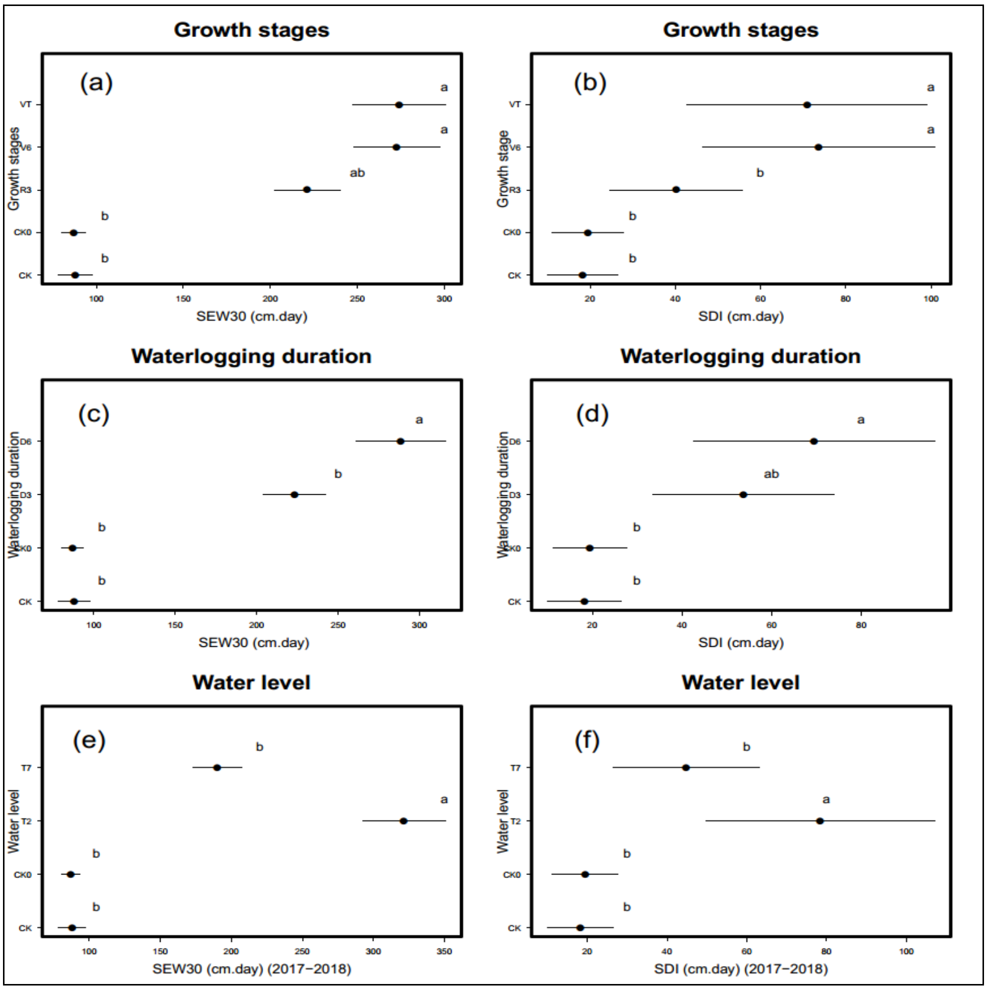


Figure 3.3. Excess water stress factor (SEW30) and Stress Day Index (SDI) variation by growth stage (a) (b), waterlogging duration (c) (d) and water levels (e) (f).*

** CK = Control with barriers; CK0 = Control without barriers; V6 = Six-leave stage; VT = Tasselling stage; R3 =Milky stage; D3 = 3 days of waterlogging; D6 = 6 days of waterlogging; T2 = water level at 2-3cm above the soil surface; T7= water level at 7-8cm above the soil surface; "a" means that the value is part of the group of the highest values, "b" means that the value is lower than the highest values at 95% confidence interval, "ab" means that the value is both similar to the values of the group a and b at 95% confidence interval; Parameter with the same letter a or b are similar at 95% confidence interval*.

3.1.2. Effects of waterlogging on maize height, leaf area index (LAI) and flowering

The analysis of variance showed that the plants' height was significantly affected at every growth stage where the waterlogging occurred from 45 DAS to the end of the growth cycle. In fact, for waterlogging at V6 stage, plant height was reduced by 10% 60 DAS and 75 DAS, and the reduction reached 17% after 6 days water stagnation. At VT stage, the 2cm-above-surface water level has reduced the height by 5% and 5.5%, 75 DAS compared to the control treatment and the 7-8 cm level above surface (Table 3.1). With 3 or 6 days of submersion the LAI reduction was at least 11% at VT stage (60 DAS), and 16% at V6 stage in case of 6 days of submersion (60 DAS). At 75 DAS, the LAI continued to decrease for plants flooded at VT stage by 31% but the LAI decrease of plants flooded at V6 stage, has been reduced by 19%. Flooded for 6 days at V6 stage, the date of flowering was delayed for 2 days (Table 3.1).

Table 3.1: Results of the analysis of variance of height, LAI and flowering date of Obatampa cultivar

Factors	Height				LAI			Flowering (DAS)
	30 DAS	45 DAS	60 DAS	75 DAS	30 DAS	60 DAS	75 DAS	
Water Level (WL)								
CK0	83.3	170.4	234.5	238.6	0.9	4.9	3.5	51.1
CK	84.1	180.2	241.3	240.9	1.0	4.7	3.4	51.9
T7	96.7	183.3	244.4	242.7	1.2	4.7	3.7	51.3
T2	91.2	174.4	227.3*	229.3*	1.2	4.2	2.9	52.3
Waterlogging Duration (D)								
CK0	83.3*	170.4 *	234.5	238.6	0.9	4.9	3.5	51.2
CK	84.1*	180.2	241.3	240.9	1.0	4.7	3.4	51.9
D3	99.0	186.6	242.7	243.2	1.2	4.7	3.3	51.3
D6	88.8 *	171.1 *	229.0	228.9 *	1.1	4.2	3.3	52.2
Growth Stage (GS)								
CK0	83.3	170.4	234.5	238.6	0.9	4.9	3.5	51.2
CK	84.1	180.2	241.3	240.9	1.0	4.7	3.4	51.9
V6	95.1	160.4 *	216.2 *	216.4 *	1.2	4.5 *	3.6	52.2
VT	93.2	185.4	242.3	240.8	1.1	3.8	2.6 *	51.6
R3	93.5	190.8	248.9	250.9	1.2	5.0	3.6	51.5 *
GS:D								
CK0	83.3	170.4 *	234.5	238.6	0.8 *	4.9	3.5	51.2 *
CK	84.1	180.2	241.3	240.9	1.2	4.7	3.4	51.9 *
R3:D3	98.1	196.6	252.2	255.1	1.2	4.9	3.5	52.1 *
R3:D6	88.8	185.2	245.7	246.7	1.2	5.2	3.7	50.9 *
V6:D3	101.7	173.7 *	230.6 *	232.6	1.3	5.0	3.6	50.6 *
V6:D6	88.5	147.1 *	201.9 *	200.2 *	1.1	3.96*	3.6	53.8
VT:D3	97.3	189.5	245.2	241.8	1.2	4.2 *	2.7 *	51.2 *
VT:D6	89.2	181.2	239.4	239.7	1.1	3.4*	2.5 *	52.0 *
WL:D								
GS:WL								
GS:WL:D								

*WL= Waterlogging level; D= Waterlogging Duration; GS= Growth Stage; GS:D = Interaction growth stage and waterlogging duration; WL:D= Iinteraction waterlogging level and waterlogging duration; GS:WL= Interaction growth stage and waterlogging level; GS:WL:D= Interaction growth stage waterlogging level and waterlogging duration; DAS= Day after sowing; CK = Control with barriers; CK0 = Control without barriers; V6 = Six-leave stage; VT = Tasselling stage; R3 =Milky stage; D3 = 3 days of waterlogging; D6 = 6 days of waterlogging; T2 = water level at 2-3cm above the soil surface; T7= Water level at 7-8cm above the soil surface; * significantly lower than the other values of the same factor at the specific date after sowing at the threshold of 5%.*

3.1.3. Effects on aboveground biomass and grain productivity

The biomass of maize *Obatampa*, on the plots flooded at V6 and VT, was significantly decreased by 35% and 20% at 68 DAS and at harvest, the reduction reached 42% and 22% respectively. At VT stage, 3 days of water stagnation were enough to reach the aforementioned rate of reduction. However, at V6 stage, 6 days soil waterlogging could produce the same rate of biomass reduction (Figure 3.4). Adversely, when plots are waterlogged at R3 stage, there was a small increase (0.3-0.8 %) in above ground biomass.

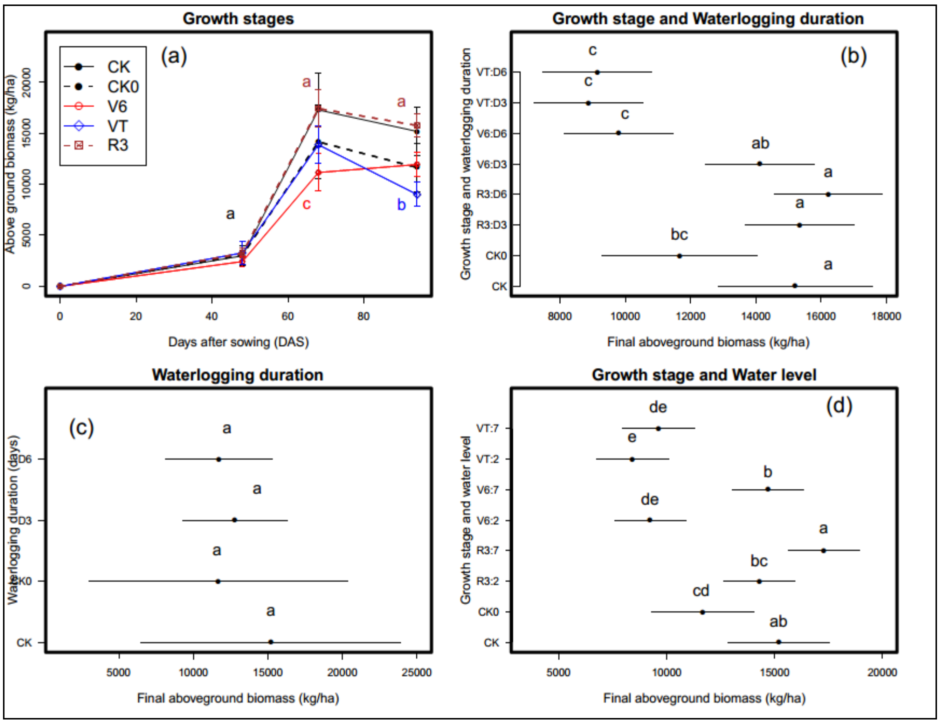


Figure 3.4. Aboveground biomass variations observed during the experiment on growth stages exposured to waterlogging (a), on growth stage and waterlogging duration (b), on waterlogging duration (c) and on growth stage and water level (d)

CK = Control with barriers; CK0 = Control without barriers; V6 = Six-leave stage; VT = Tasselling stage; R3 =Milky stage; D3 = 3 days of waterlogging; D6 = 6 days of waterlogging; V6:D3 = Interaction between six-leave stage and 3 days of waterlogging; V6:D6 = Interaction between six-leave stage and 6 days of waterlogging; VT:D3 = Interaction between tasselling stage and 3 days of waterlogging; VT:D6 = Interaction tasselling stage and 6 days of waterlogging; R3:D3 = Interaction between milky stage and 3 days of waterlogging; R3:D6 = Interaction milky stage and 6 days of waterlogging; V6:2 = Interaction between six-leave stage and 2-3cm of water level above the soil surface; V6:7 = Interaction between six-leave stage and 6-7cm of water level above the soil surface; VT:2 = Interaction between tasselling stage and 2-3cm of water level above the soil surface; VT:7 = Interaction between tasselling stage and 6-7cm of water level above the soil surface;R3:2 = Interaction between milky stage and 2-3cm of water level above the soil surface; R3:7 = Interaction between milky stage and 6-7cm of water level above the soil surface; "a" means that the value is part of the group of the highest values, "b" means that the value is lower than the highest values at 95% confidence interval; "c" means that the value is lower than the values of group "b" at 95% confidence interval; "d" means that the value is lower than the values of group "c" at 95% confidence interval; "e" means that the value is lower than the values of group "d" at 95% confidence interval; "ab", "bc", *"cd", "de" respectively mean that their values are both similar to the values of the group a and b; b and c; c and d , d and e at 95% confidence interval; Parameter' values with the same letter are similar at 95% confidence interval.*

The grain yield was drastically reduced by flooding at VT stage. Hence, 3 and 6 days of submersion, at 2-3 cm and 7-8 cm above surface water level have shortened the grain filling period and reduced the grain production by at least 53% as compared to the control plots' grain yield estimated at 5.23 $t.ha^{-1}$ (Figure 3.5). At V6 stage, 6 days of submersion reduced the yield by 31% but after 3 days of submersion, it increased by 9%. Moreover, a little increase of the grain yield by 12% and 3% was observed for maize flooded during 3 or 6 days at R3 stage (Figure 3.5).

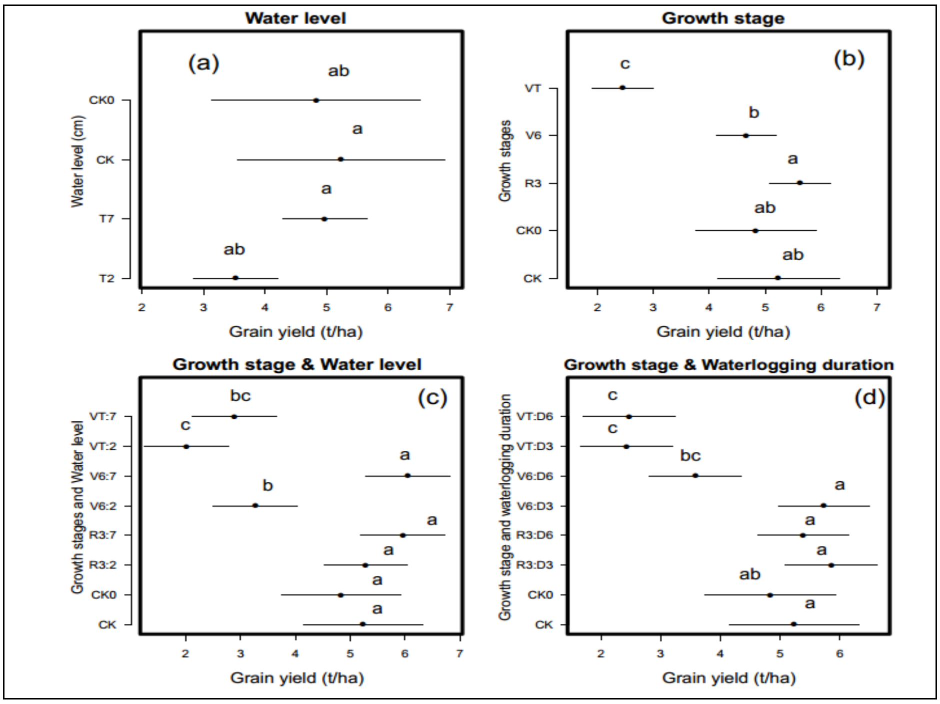


*Figure 3.5.Grain yield variations observed during the experiment on water level (a), growth stage (b), growth stage and water level (c), growth stage and waterlogging duration (d)**

**CK = Control with barriers; CK0 = Control without barriers; V6 = Six-leave stage; VT = Tasselling stage;R3 =Milky stage; T2 = water level at 2-3cm above the soil surface; T7= water level at 7-8cm above the soil surface; V6:D3 = Interaction between six-leave stage and 3 days of waterlogging; V6:D6 = Interaction between six-leave stage and 6 days of waterlogging; VT:D3 = Interaction between tasselling stage and 3 days of waterlogging; VT:D6 = Interaction tasselling stage and 6 days of waterlogging;R3:D3 = Interaction between milky stage and 3 days of waterlogging; R3:D6 = Interaction milky stage and 6 days of waterlogging; V6:2 = Interaction between six-leave stage and 2-3cm of water level above the soil surface; V6:7 = Interaction between six-leave stage and 6-7cm of water level above the soil surface; VT:2 = Interaction between tasselling stage and 2-3cm of water level above the soil surface; VT:7 = Interaction between tasselling stage and 6-7cm of water level above the soil surface; R3:2 = Interaction between milky stage and 2-3cm of water level above the soil surface; R3:7 = Interaction between milky stage and 6-7cm of water level above the soil surface; "a" means that the value is part of* *the group of the highest values, "b" means that the value is lower than the highest values at 95% confidence interval; "c" means that the value is lower than the values of group "b" at 95% confidence interval; "ab", "bc", respectively mean that their values are both similar to the values of the group a and b; b and c; c and d , d and e at 95% confidence interval; Parameter' values with the same letter are similar at 95% confidence interval.*

3.1.4. Analytical estimation of loss

In an attempt to assess grain yield losses with respect to excess soil water, the Relative Yield Loss (RYL) generated from equation 6 (Chapter 2, section 2.2.3) was regressed against the excessive water index (SDI). Considering all the tested growth stages (V6, VT and R3) and the control plot CK, an exponentially negative relationship was found between SDI and grain yield losses. The coefficients of determination (R^2 = 0.6 and 0.7) were tested statistically significant. Figure 3.6 shows the relationship between yield loss and SDI.

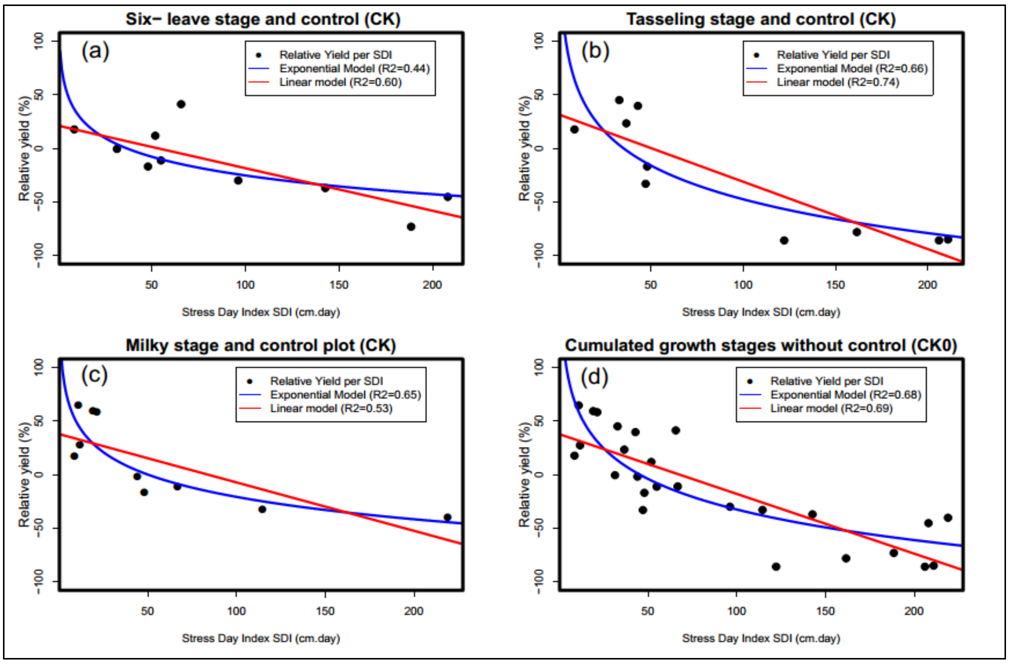


Figure 3.6. Relationship between Stress Day Index (SDI) and maize (Obatampa cultivar) yield loss in case of flooding at six-leave stage (a), at tasselling stage (b) at milky stage (c) and the combination of all the three phenological stages during 2017/2018 at Boassa, Ouagadougou, Burkina Faso

3.1.5. Concluding remarks

During the 2017 and 2018 rainy seasons, we investigated the temporary effects of soil waterlogging and water stagnation on *Obatampa* cultivar under ambient field conditions. The trials took place on a farm but artefact conditions were created to increase flooding potentials and reduced surface and sub-surface drainage. The experiments consisted of 42 randomized treatments including two controls, 3 repetitions of two water stagnation (1-3 days and 4-6 days), two water levels (2-3 cm and 7-8 cm levels above-surface) and three different phenological stages of maize *Obatampa*. The results show that hypoxia (1-3 days of waterlogging) and anoxia (4-6 days of waterlogging), respectively reduced significantly the grain yield at tasselling stage. At six leave stage, only the anoxia significantly reduced the grain yield. Moreover, the grain yield loss decreases with the stress day index (SDI). Hence, SDI can be used to monitor temporarily maize field flooding under crop insurance scheme against excess water stress in the current context of climate change in the West African Sahel.

3.2. Spatiotemporal variation of maize growth and productivity on a floodplain

The section 3.2 describes the results obtained from the trials on uncontrolled waterlogging and summarizes them in a short concluding and remarks. The results are detailed according to the: (i) soil water level dynamics in the floodplain of Aniabisi; (ii) cumulated effects of continuous waterlogging on maize growth and development and (iii) cumulated effects of continuous waterlogging on above ground biomass and grain yield.

3.2.1. Soil water level dynamics in a floodplain: case of Aniabisi

The analysis of water level fluctuation in the 0.30 m depth of topsoil during the experimental years (2017 and 2018) showed during 2018, a more exposure of the trial to waterlogging, with 583.2 mm and 627.3 mm as cumulative rainfall during the two cropping season. According to the observed depth of the water level (considering to the soil surface as reference), respectively on plots with bunds and plots without bunds, located in downslope and middle slope in 2017 (-9.2 cm; -13.6 cm; -16.5 cm; -20.9 cm) were lower than the depths reached during 2018 (+ 6.7 cm; -1.7 cm; -4.7 cm; -6 cm; 7 cm) (Figure 3.7 a and Figure 3.7 c). Moreover, the frequencies of the water level in the 0.15 m depth of topsoil, on plots with bunds and plots without bunds, located in downslope and middle slope during 2017 cropping season (58%, 34%, 25%, 4%) were also lower than the frequencies observed in 2018 (63%, 57%, 45%, 23%). It appears clearly that, the exposure to waterlogging depended of the topographical location of the plots. During the two-year experiment, upslope plots were less exposed to waterlogging, compared to plots located at middle and downslope. The bunds surrounding certain plots reduced the runoff and thus, have increased the water level reached duration of the natural waterlogging period (Figure 3.7 b and Figure 3.7 d).

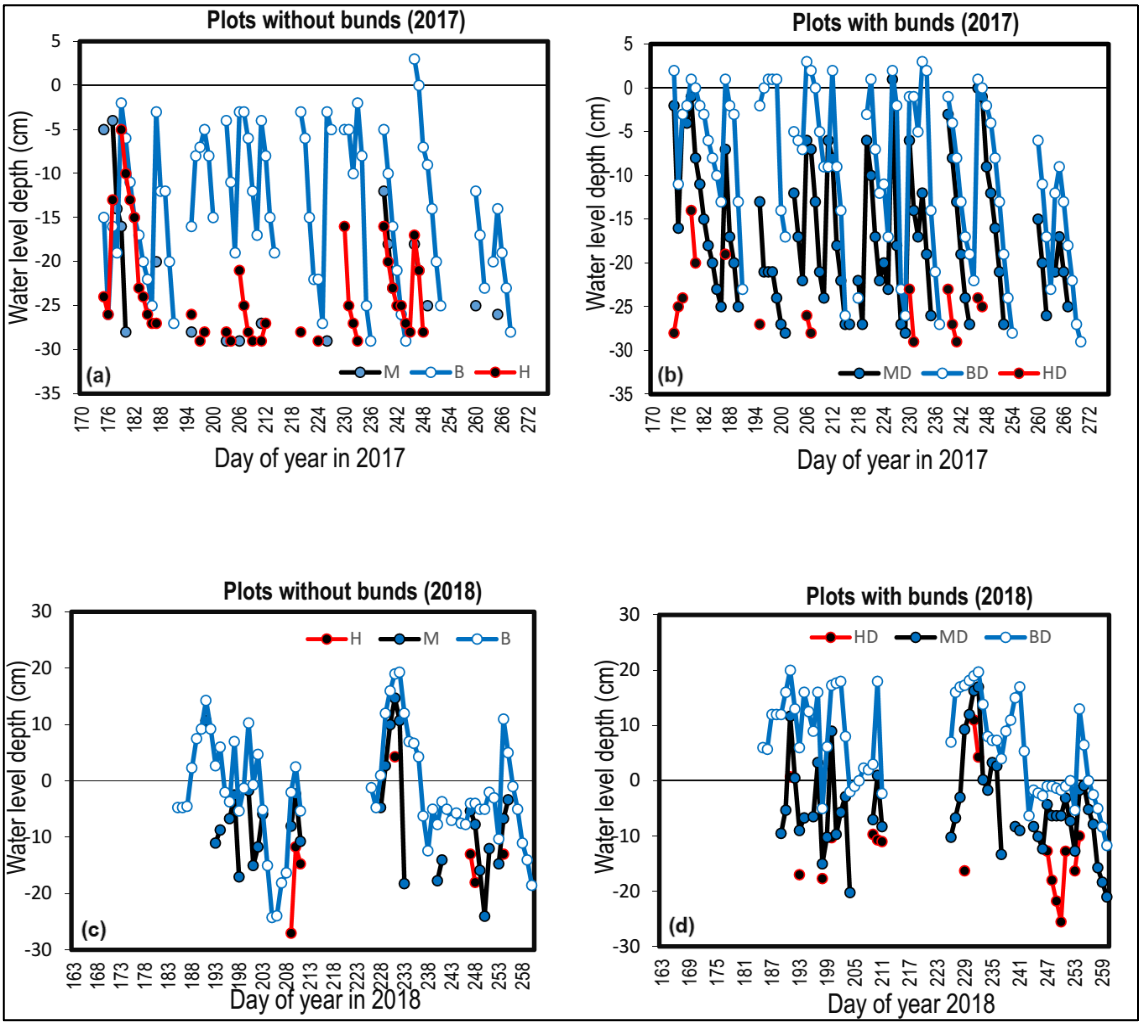


Figure 3.7. Water level dynamic in the topsoil in 2017 and 2018

H : upslope ; HD : upslope with bunds ; M : middle slope ; MD : middle slope with bunds ; B : downslope; BD : downslope with bunds

According to the excess water stress-day factor (SEW30), the risk of waterlogging on the plots located downslope and in the middle slope without bunds as barriers (173 cm.day and 1157 cm.day in 2017, 625 cm.day and 1567 cm.day in 2018) are low compared to the values reached on the downslope and mid-slope plots with bunds during the experiments (1011 cm.day and 1705 cm.day in 2017; 1154 cm.day and 1798 cm.day in 2018) (Figure 3.8 a and 3.8 b).The results also showed that waterlogging risk varied during the vegetative (7-45 DAS) and reproductive (46-91 DAS) crop growth stages according to the different sowing dates adopted each year. In 2017, plants sown on the first date were more exposed to waterlogging during their vegetative period. On the other hand, for the second planting date, only the plants located downslope with or without bunds were exposed during their vegetative phases. Plants at mid-slope and upslope have undergone more waterlogging risk during their reproductive period. In 2018, apart from the plants sowed at the second date at middle slope without bunds, all maize plots experienced an important waterlogging risk during their reproductive period (Figure 3.8 c and 3.8 d).

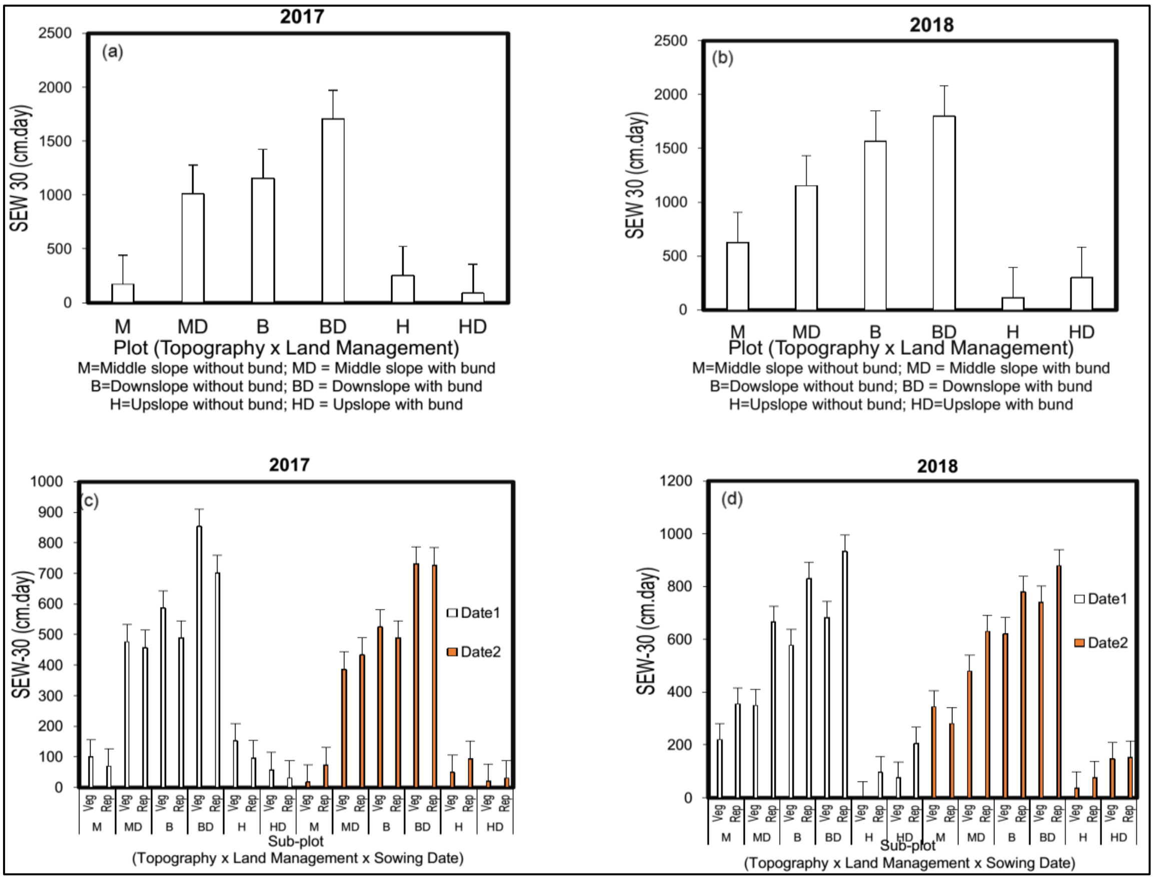


Figure 3.8. Variation of SEW30 on plots (a,b) and on sub-plot by vegerative (Veg) and reproductive (Rep) stages (c, d) in 2017 et 2018.*

**H : upslope ; HD : upslope with bunds ; M : middle slope ; MD : middle slope with bunds ; B : downslope; BD : downslope with bunds; Date 1 (19th June 2017/31st May 2018; Date 2 (3rd July 2017/21th June 2018).*

3.2.2. Cumulated effects of continuous waterlogging on maize growth and development

Statistical analysis of growth data revealed that, the presence of bunds in 2017 reduced the number of leaves and LAI by 10% and 40% respectively at 30 DAS. At 45 DAS, the number of leaves, LAI and plant height were also reduced by 11%, 41% and 23%. At 60 DAS, only the plant height was reduced by 10% due to the bunds. However, the same analysis carried out in 2018 showed that the plant height had been reduced from 10% to 12%, from 45 DAS. The number of leaves and LAI decreased significantly in plots surrounded by bunds from 17% to 29% from 75 DAS. In the case of sowing date, a comparison between seeds sown on the first sowing date (Date 1, 19th June 2017/31st May 2018) and those sown on the second sowing date (Date 2, 3rd July 2017/21th June 2018) shows that the height of the plant was reduced by 18 % at

45 DAS in 2017, because at mid-June 2017 the water level in the pipes was already in the 5cm depth of the topsoil. In the same season (2017), the number of leaves and LAI of maize planted at D1, were reduced by 8% and 22% at 60 DAS.

In 2018, the number of leaves of maize planted on Date 2 plants were considerably reduced from 10% to 19%, and from 12% to 49% at the end of the crop cycle, in the case of the LAI. The gap in the height of maize planted on Date 2, compared to those planted on Date 1, from 45 to 60 DAS, decreased from 30% to 6% (Table 3.2) relative to maize planted on Date 1 (31st May 2018).

3.2.3. Cumulated effects of continuous waterlogging on above ground biomass and grain yield

Statistical analysis of above ground biomass at 30, 60 and 90 DAS and on grain yield showed that aboveground biomass at 60 and 90 DAS and grain yield depended significantly on the position of plots with respect to topography in 2017 (Figures 3.9 a and 3.9 d). In 2018, the grain yield was also strongly influenced by the topography, but at the opposite of 2017 result, only the aboveground biomass at 30 DAS was affected by the topographic position (Figures 3.9 b and 3.9 d). At 30 DAS, in 2018, the aboveground biomass on the downslope plots was reduced by 21% compared to the upslope plots. In 2017, at 60 and 90 DAS, the biomass losses on downslope plots were estimated at 78% and 89% lower than the upslope plots. Considering the two experimental years, a low grain yield was obtained on downslope plots (0.39 $t.ha^{-1}$ in 2017 and 1.11 $t.ha^{-1}$ in 2018). This represented a 91% (2017) and 62% (2018) losses in comparison to upslope. The bunds easily reduced dry biomass accumulation during the crop cycle in 2017 but had no effect in 2018. The biomass at 60 DAS was very sensitive to the sowing date adopted in 2017 and 2018. During 2017, the second sowing date almost doubled the biomass at 60 DAS compared to the first sowing date. In addition, the grain yield was increased by 64% for second sowing date. Conversely, in 2018, the second sowing date had significantly reduced the biomass by 25% at 60 DAS, without any significant effect on grain yield (Figure 3.9 c).

Table 3.2: Number of Leaves (nf), leaf area index (LAI) and plant height (h) at different date after sowing during 2017 and 2018

Factor	30 DAS						45 DAS						60 DAS						75 DAS			90 DAS		
	2017			2018			2017			2018			2017			2018			2018			2018		
	nf	LAI	H	nf	LAI	h	nf	LAI	h	nf	LAI	h	Nf	LAI	H	nf	LAI	h	nf	LAI	h	nf	LAI	h
Topography																								
Upslope	6.6a	0.6a	29a	8.5a	1.7a	57a	9.7a	2.8a	106a	9.1a	2.7a	112a	9.1a	1.9a	151a	9.4b	2.5a	147a	6.6a	1.6a	153a	5.5a	1.2a	164a
Middle slope	6.4a	0.5a	26a	9.7a	2.1a	54a	8.9a	1.9b	90a	8.5a	2.0a	93 a	8.9a	2.2a	150a	9.9a	2.5a	142a	4.3b	0.9b	147a	2.4b	0.4b	152a
Downslope	5.0b	0.2b	21b	9.1a	1.8a	47a	5.7b	0.4c	42b	8.6a	2.1a	95a	6.6b	0.6b	65b	8.8c	3.3a	145a	4.7b	1.1ab	149a	2.8b	0.6b	156a
Land Management																								
With Bund	5.7b	0.3b	24a	8.7a	1.7a	52a	7.6b	1.3b	69b	8.4a	2.2a	94b	8.4a	1.5a	116b	9.2a	2.8a	135b	4.7b	1.0b	141b	3.4b	0.7b	149b
Without Bund	6.4a	0.5a	27a	9.5a	2.0a	54a	8.5a	2.2a	89a	9.1a	2.3a	105a	8.0a	1.7a	128a	9.6a	2.7a	154a	5.7a	1.4a	158a	3.8a	0.8a	166a
Sowing Date																								
Date 1	6.3a	0.4a	26a	8.7a	1.8a	51a	8.3a	1.5a	71b	9.5a	2.7a	118a	7.8b	1.4b	119a	10.4a	3.7a	150a	5.6a	1.3a	149a	3.8a	0.8a	155a
Date 2	5.7b	0.4a	25a	9.5a	1.9a	55a	7.9a	1.9a	87a	8b	1.8b	82b	8.5a	1.8a	126a	8.4b	1.9b	140b	4.7b	1.1b	150a	3.4b	0.7b	160a

"a" means that the value is part of the group of the highest values, "b" means that the value is lower than the highest values at 95% confidence interval; "ab" mean that their values are in both groups a and b; Parameter' values with the same letter are similar at 95% confidence interval.

Interaction between sowing date and topography also significantly affected biomass at 60 DAS and grain yield in 2017. The biomass at 60 DAS and grain yield were significantly reduced on downslope plots for both the Date 1 and the Date 2 sowing date. In 2017, the presence of bunds and sowing date also interacted and affected the grain yield. The bunds installed for the maize sowed at Date 1, reduced the yield to 1.7 $t.ha^{-1}$, but installed for maize sowed at Date 2, those bunds had increased grain yield to 4.1 $t.ha^{-1}$.

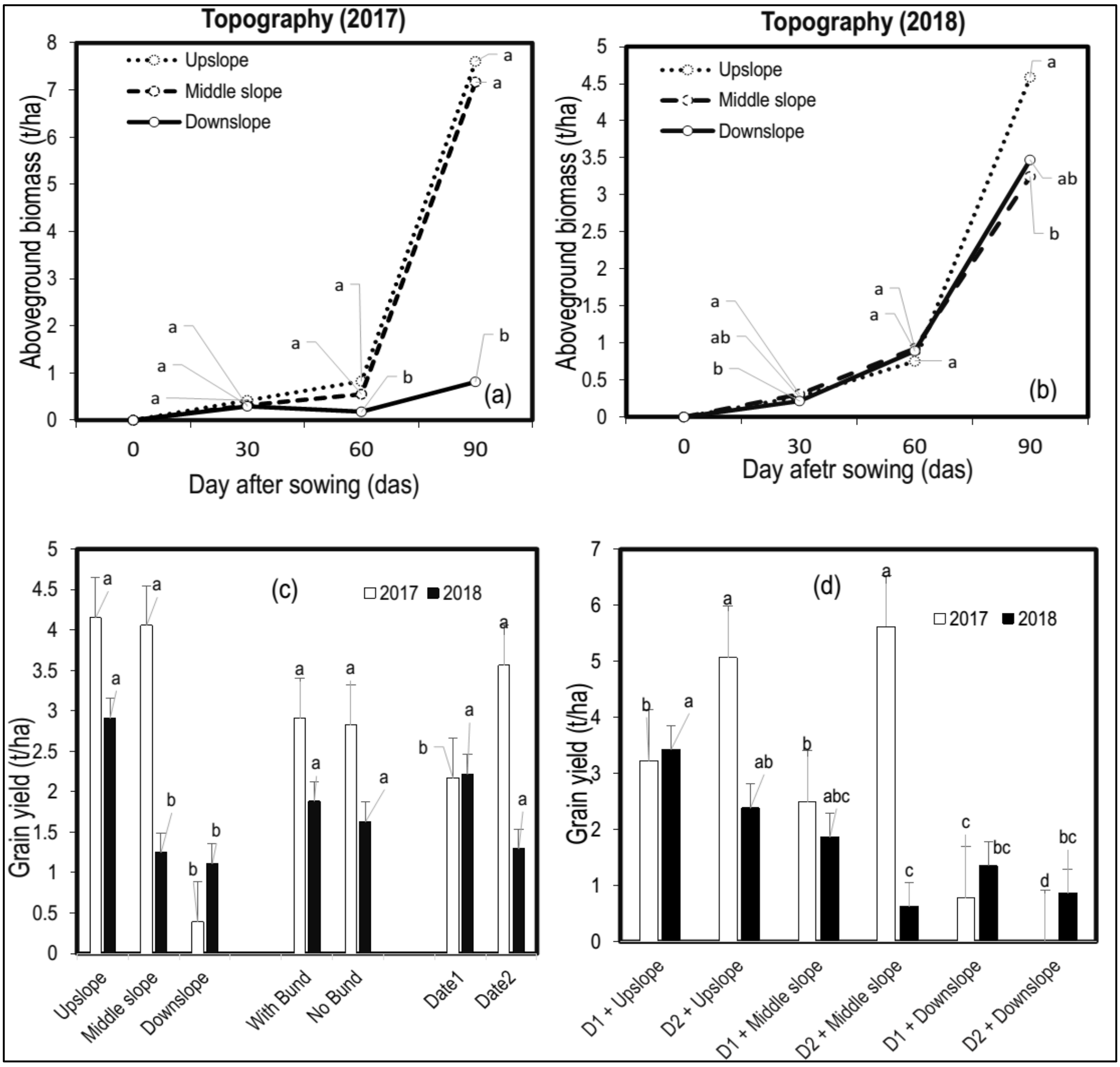


Figure 3.9. Above ground biomass and grain yield (2017 and 2018).

"a" means that the value is part of the group of the highest values, "b" means that the value is lower than the highest values; "c" means that the value is lower than the values of group “b”; "ab", “bc”, “abc” respectively mean that their values are both similar to the values of the group a and b; b and c; a b and c, at 95% confidence interval; Differences and similarities are significant at 95%according to Fisher and Duncan tests.

Exponentially negative relationship was found between grain yield and excess water stress factor (SEW30) were found out for each season and crop growth period (Figure 3.10). During 2017, the SEW30 index and grain yield were negatively correlated (-0.85) with the cumulative SEW30 of the vegetative period (Fig 3.10 b). Considering the vegetative and reproductive periods of the experiment conducted in 2017, there is a considerable decline of grain yield respectively from 200 cm.day for the vegetative stage and 100 cm.day at the reproductive stage. Waterlogging seems to have been a major constraint for maize productivity during 2017, when the waterlogging risk were important during the vegetative phase than during the maize reproductive phase (Figures 3.10 b and 3.10 c). However, during 2018, despite the more important waterlogging risk compared to 2017, the correlation between SEW30 and grain yield was completely low compared to those obtained in 2017.

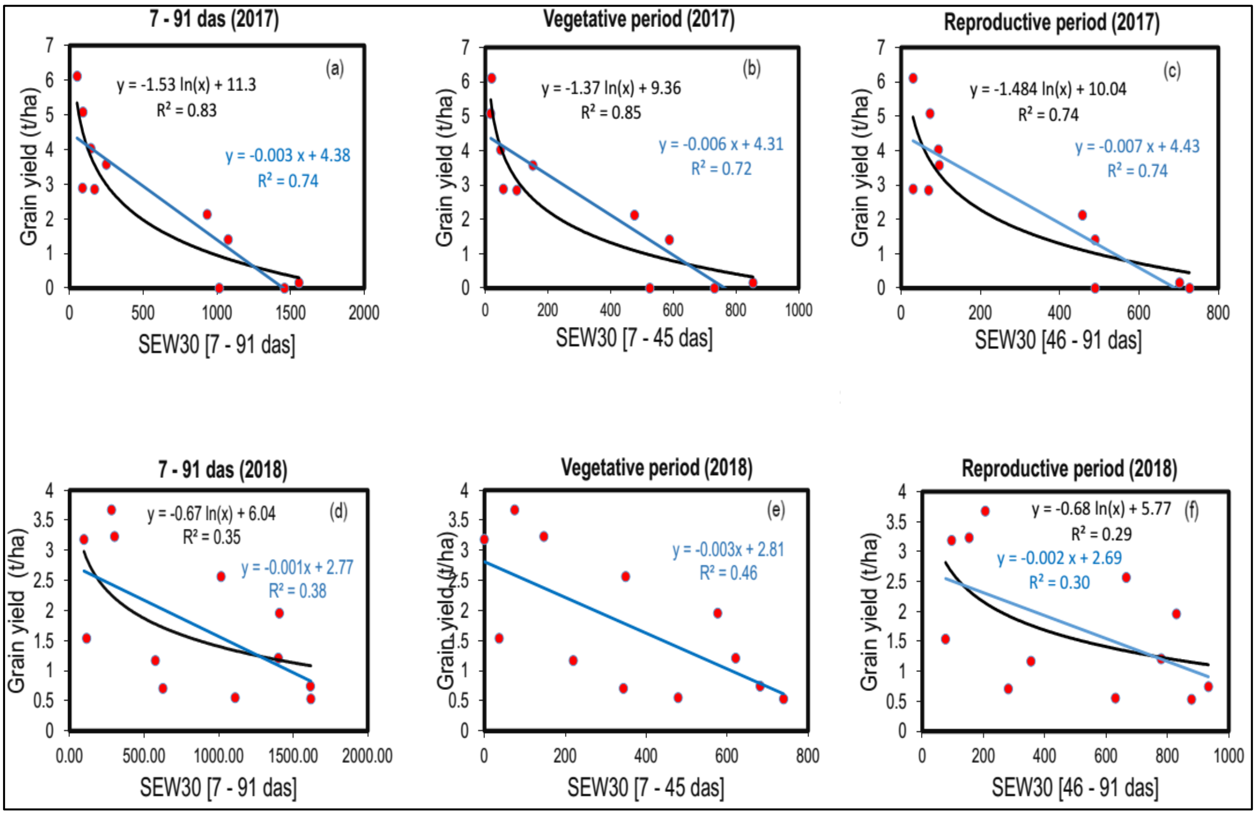


Figure 3.10. Grain yield variation according to cumulative water stress-day factor (SEW30).

3.2.4. Concluding remarks

The results showed that topographical position is the main factor in the exposure to soil waterlogging and location in downslope can induced yield losses about 62% and 91% compared to the upslope yield. Sand bunds easily increase soil waterlogging in floodplain already prone to it. During 2017 and 2018, the sowing date that help to avoid the *Wang-data* maize cultivar to be exposed to waterlogging during its vegetative period, has improved the crop growth and productivity. Under natural conditions, cumulative soil waterlogging can significantly impact maize growth, apart from the potential use of SEW30 for yield loss assessment in cumulative soil waterlogging adaptation measures such as early sowing (tested in 2018) combined with a seasonal forecasting can contributed to the reduction of damages induced by natural and uncontrolled flooding in the area prone to flooding in West African Sahel.

3.3. Crop model simulations of maize growth, development and productivity under waterlogging stress

This section describes the results of the calibration and the validation of EPIC model and summarized them in a short concluding and remarks. The results are detailed according to three sub-sections: (i) water dynamics and waterlogging period's simulations; (ii) leaf area index, biomass growth and yield under waterlogging conditions (iii) simulated excessive water indices and yield losses under waterlogging at different growth stages conditions.

3.3.1. Water dynamics and waterlogging periods simulations

In section 3.1, we showed that bunds combined with plastic tarpaulin had no significant effect on the exposure of the control plots (CK and CK0) to waterlogging. Indeed, the simulations of controls over the experimental years, showed a soil moisture variation between the soil wilting point and field capacity in the 29 cm depth of topsoil. The saturation point was not reached on controls during the experiment. Except the cases of long dry periods, the trends of simulated soil moisture in the topsoil of controls plots with barriers (CK) and without barriers (CK) were similar over the experiment. Indeed, lateral hydraulic conductivity modification has increased the diffusion of water in the topsoil but also seems to increase the soil moisture loss during long dry period that occurs at the end of the season (Figure 3.11 a, b). Without flooding periods, and despite the several water level observed data in 2018, the correlation between simulated soil moisture and water level was weak, compared to the highly correlation observed ($r \geq 0.7$; p-value ≤ 0.05), in cased of induced waterlogging, except for T7D6VT in 2017.

For the hypoxia induced at V6 stage with 2 or 7 cm of water above the soil surface (T2D3V6, T7D3V6), the flooding was less efficient in 2017 compared to 2018. In the case of those treatments, the saturation point of soil was reached at the second date of flooding in 2017 but the soil was supersaturated in 2018, during the 3 days of flooding (Figures 3.11 c; i). The model was able to simulate the minimum of irrigation volume which is needed for triggering the daily soil waterlogging over the cropping seasons (Figures 3.11 d, e, f, g, h, i, j, m, n).

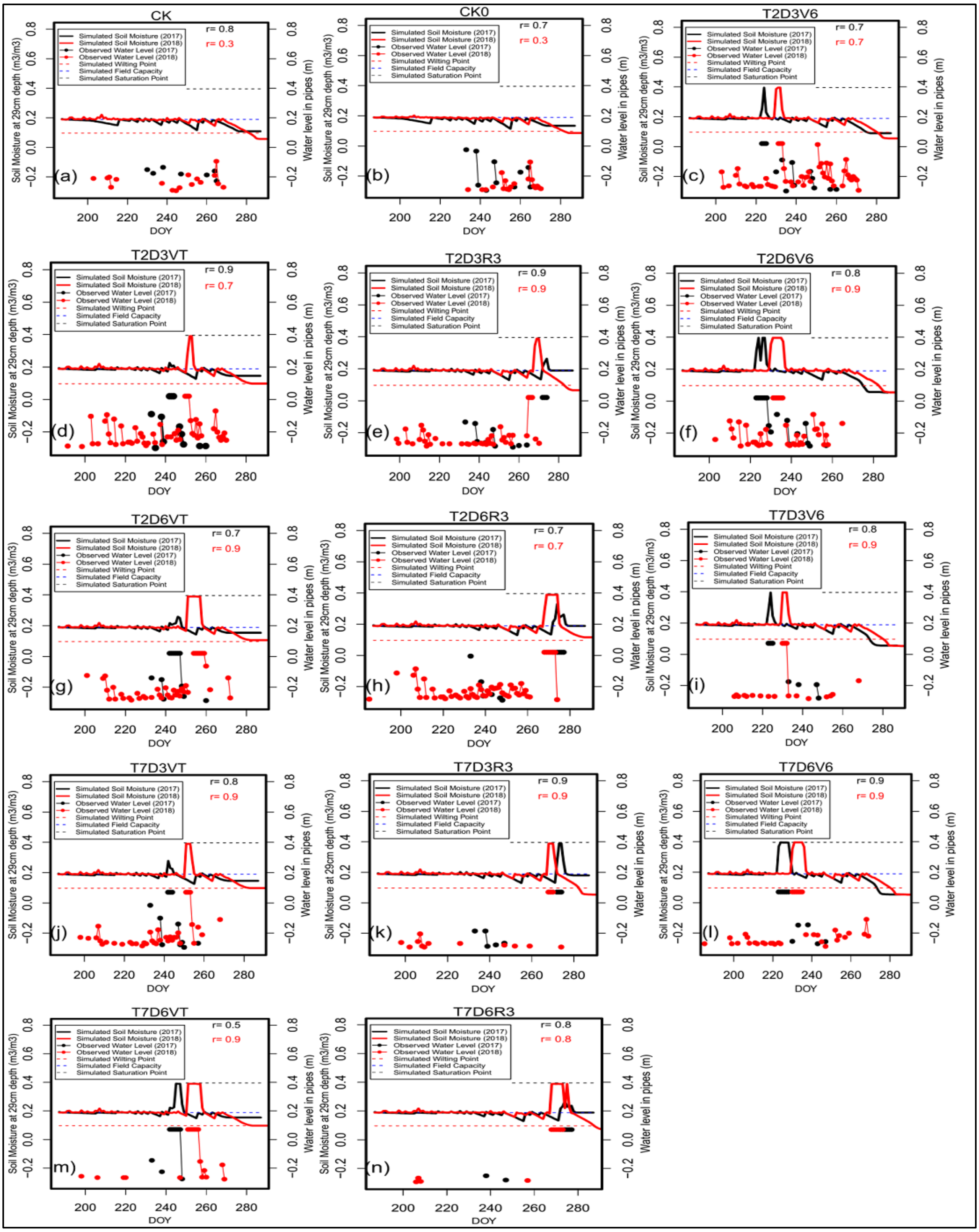


Figure 3.11. Observed water level and simulated soil moisture in 29cm depth of topsoil during the experimentation

* *CK ; T2D3V6; T2D3VT ; T2D3R3; T2D6V6; T2D6VT; T2D6R3; T7D3V6; T7D3VT; T7D3R3; T7D6V6; T7D6VT; T7D6R3 detailled in section 2.1.1.*

According to the soil moisture simulations of Aniabisi' upslope, the construction of bunds has no significant effect on soil moisture trends compared to the difference induced by the different sowing date application. Under natural flooding conditions of Aniabisi during 2017, the trends of observed water level and simulated soil moisture were similar but relationship between observed water level in the pipes and simulated soil moisture at 30 cm depth was weak at upslope (where plots were not flooded) and at downslope (where plots were flooded), (Figure 3.12 a, b, c, d). Although the similarity of the trends, the weakness of the correlation between the simulated soil moisture and observed water level from the pipes, was due to a 1 day delay observed between their trends (between 08 august (220^{th} day of year) and 28 august (240^{th} days of year)) (Figure 3.12 c, d). Indeed, the model computes on daily basis at the end of day the water balance. It means that the effects of a rain that occurs on day “i” is simulated by the model on the day “i+1” but rain events that occurred early in the morning were captured by the pani pipe.

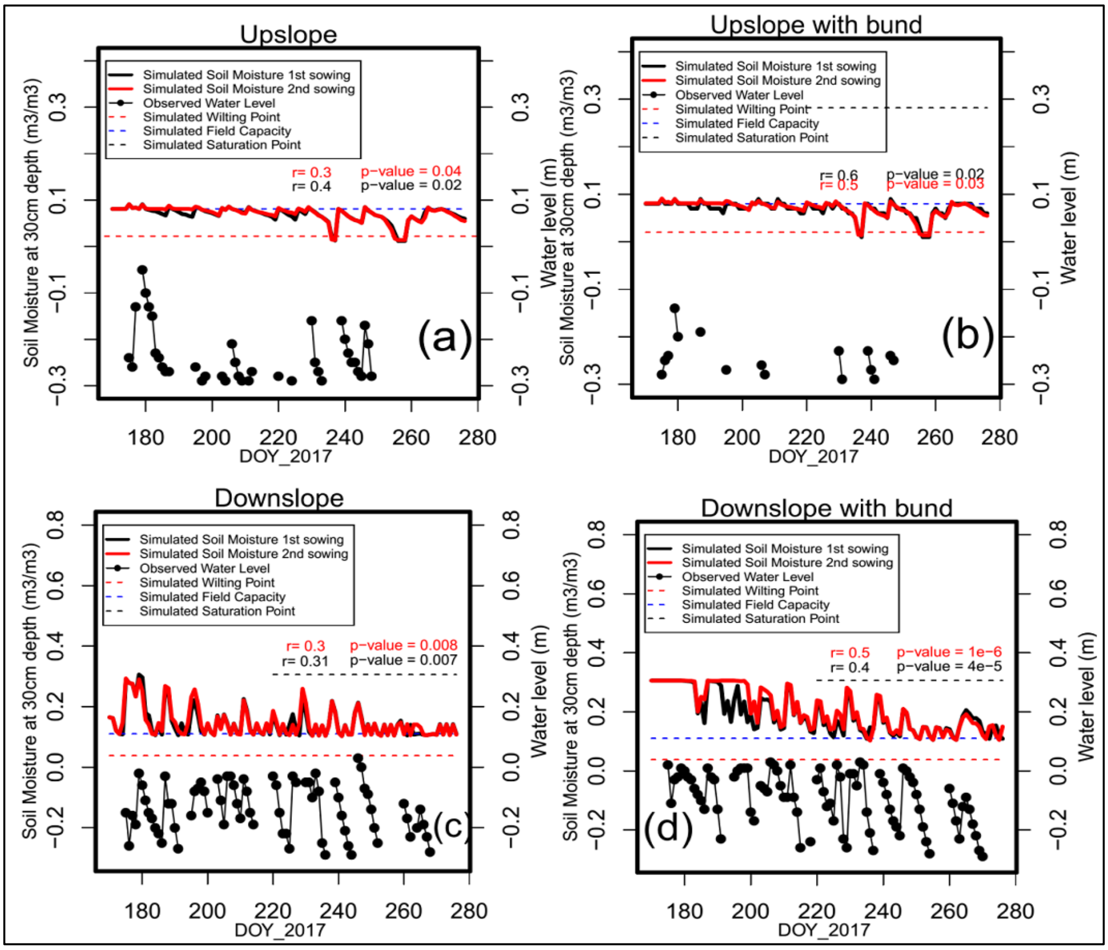


Figure 3.12. Simulation of soil waterlogging periods on plots located at upslope (a, b) and downslope (c,d) during 2017 at Aniabisi

3.3.2. Leaf area index, biomass growth and yield under waterlogging conditions

Broadly, the model simulated with interesting accuracy the LAI for all the treatments, except most of the treatments under anoxia at V6 and VT stages (T2D6V6, T2D6VT and T2D6VT). EPIC model, underestimated the effect of anoxia on LAI in those treatments (Figure 3.13).

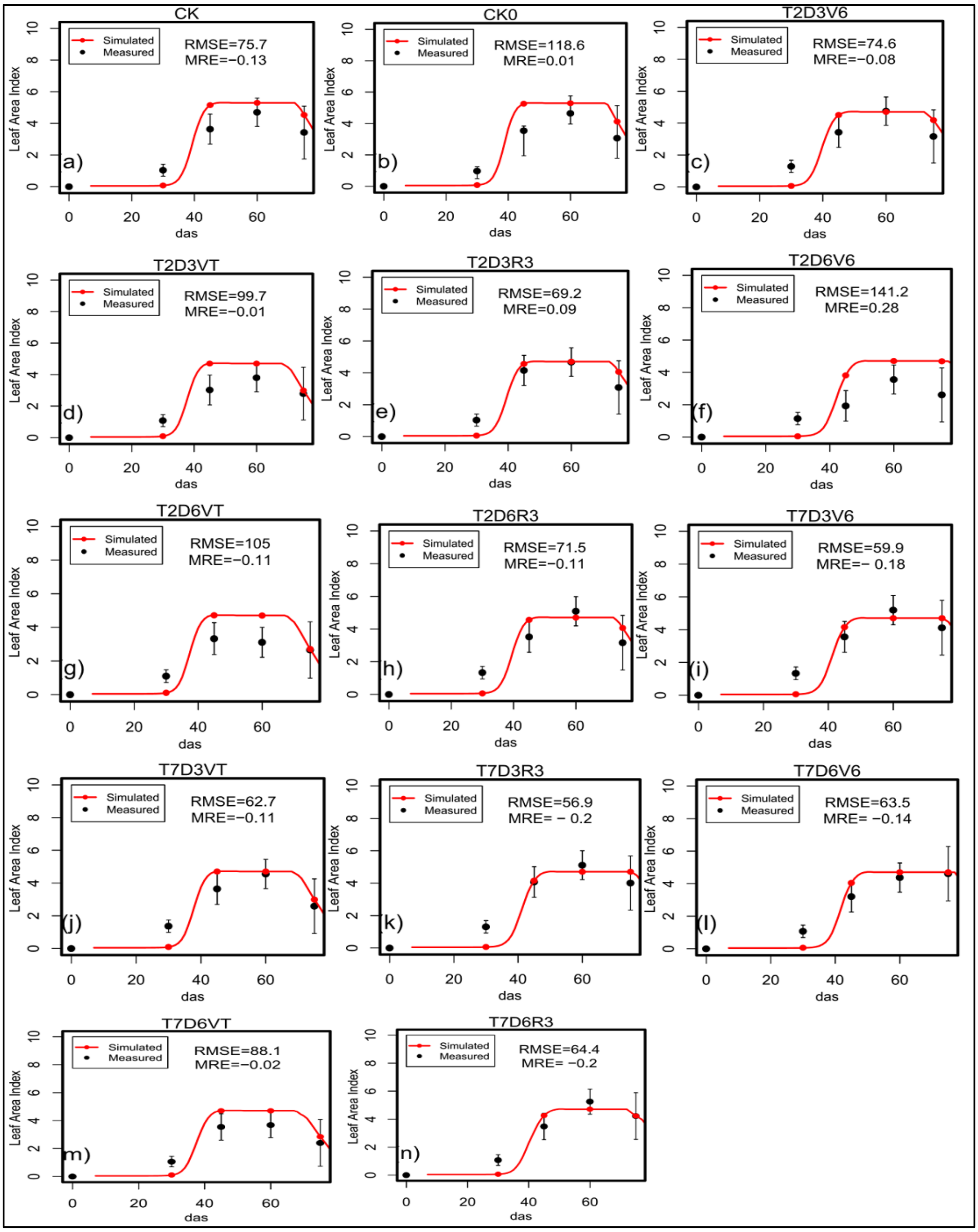


Figure 3.13. Observed and simulated leaf area index during the experimentation of Boassa

CK ; T2D3V6; T2D3VT ; T2D3R3; T2D6V6; T2D6VT; T2D6R3; T7D3V6; T7D3VT; T7D3R3; T7D6V6; T7D6VT; T7D6R3 detailled in section 2.1.1.

Indeed, in the case of Aniabisi, the model simulated with high accuracy the observed LAI at upslope (RMSE = 5.9 and 22.8 during 2017 and 2018) and at downslope when the waterlogging occurs, mostly at the end of the crop cycle (RMSE = 34.7) (Figure 3.14 a). But, in 2017, the model overestimated the LAI where the downslope plots experienced waterlogging since the beginning of the season, (Figure 3.14 b).

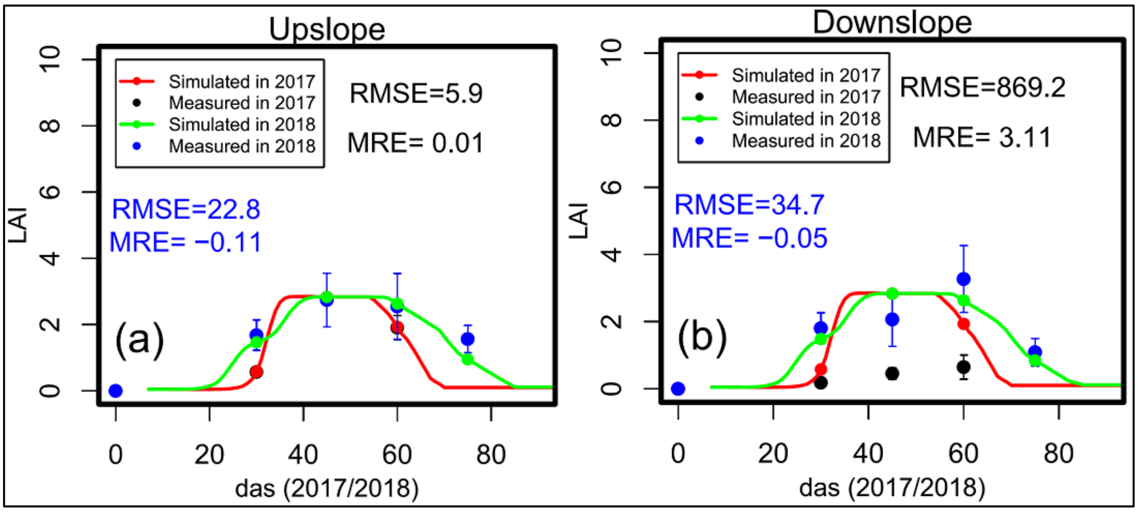


Figure 3.14. Observed and simulated leaf area index during the extensive experimentation of Aniabissi.

For the treatments including flooding with 2-3cm of water above the soil surface, the growth of aboveground biomass under hypoxia at V6 and VT stages were well simulated (Figures 3.15 c, d). The biomass losses observed in the field after the plant wilting that occurred after the waterlogging period induced a gap at 90 DAS between the simulated and the observed biomass for T2D3VT (RMSE=87.9 $t.ha^{-1}$) (Figure 3.15 d). During 2017 were the soil super saturation was not effective, the model simulated well the biomass growth (RMSE=9.6 $t.ha^{-1}$), but in 2018, the effect of hypoxia at milky stage R3 was overestimated (RMSE=209 $t.ha^{-1}$) (Figure 3.15 e). The anoxia induced by 2-3 cm of water level above the soil surface were not well simulated for V6 and R3 stages but were well simulated at VT stage. The model underestimated the effect of anoxia on the growth when it's occurred at V6 stage but over estimated its effect at R3 stage (Figures 3.15 f, g, h). In case of 7-8 cm of water level above the soil surface, the effect of hypoxia on biomass was not well simulated for V6, VT and R3 stages (Figure 3.15 i, j, k). For all the rest of tested growth stages with 7cm of water above the soil surface, the model were overestimated the effects of anoxia except under anoxia, except for VT and V6 stages (Figures 3.15 l, m).

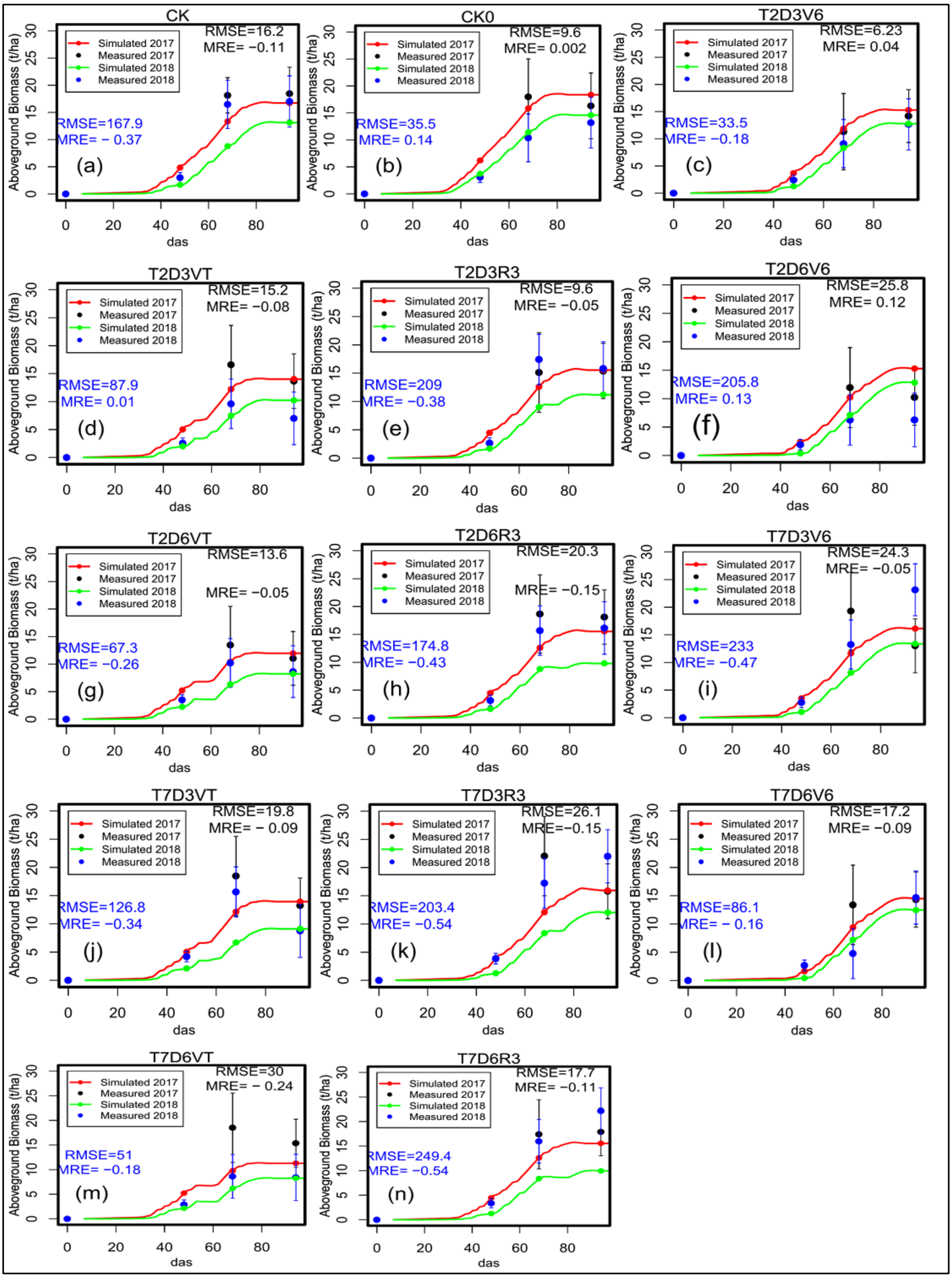


Figure 3.15. Observed and simulated aboveground biomass during the experimentation

CK ; T2D3V6; T2D3VT ; T2D3R3; T2D6V6; T2D6VT; T2D6R3; T7D3V6; T7D3VT; T7D3R3; T7D6V6; T7D6VT; T7D6R3 detailled in section 2.1.1.

Under natural waterlogging periods of Aniabisi, the average final aboveground biomass at upslope over 2017 and 2018 were well simulated but there is a gap, at 60 DAS between simulated and observed aboveground biomass (Figure 3.16 a). At downslope, in 2017, the model underestimated the effects of long-term waterlogging that occurs since the vegetative phases on the biomass at 60 DAS but the final biomass was well estimated. During 2018, the model overestimated the effects of excessive soil moisture on the final biomass (Figure 3.16 b).

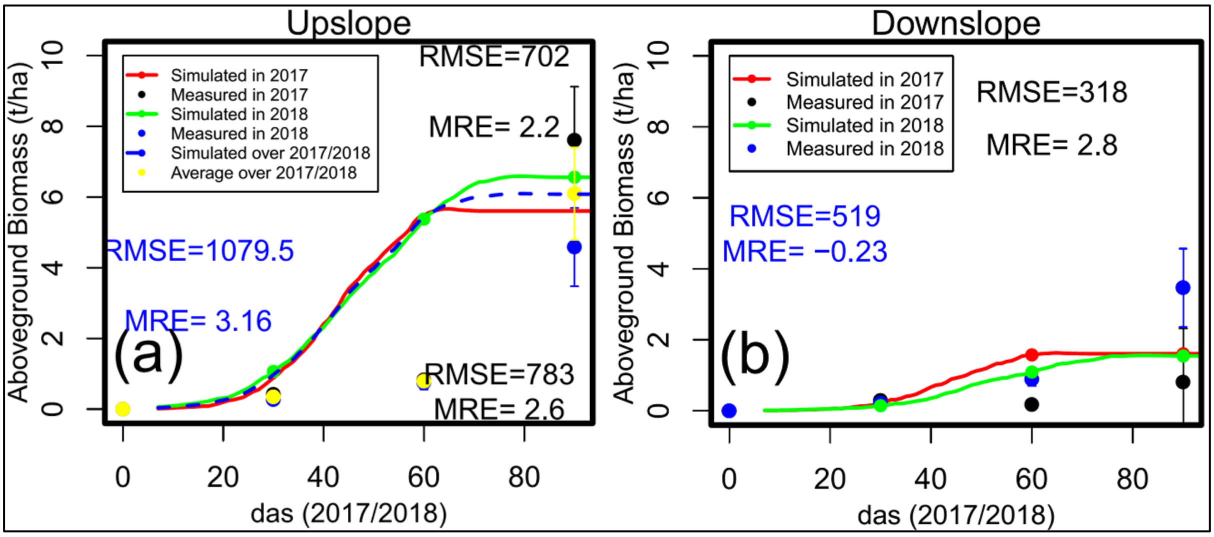


Figure 3.16. Aboveground biomass growth at upslope (a), downslope (b) and grain yield during 2017 and 2018 at Aniabisi

The performance for the yield simulation in the case of controls was good (Figure 3.17 a). Yield reduction due to hypoxia under 2 cm of water above the soil surface was well simulated for V6 and R3 stages, but the model underestimated the yield suppression effect that occurred at VT stage. For the anoxia induced by 2 cm of water above the soil surface only its effect on yield at R3 stage was well simulated for stages R3. The model underestimated its effect at V6 and VT stages. For the treatments flooded with water level at 7cm above the soil surface, the hypoxia effects at R3 and the anoxia effects at V6, VT and R3 are well simulated. The model overestimated the hypoxia effects at V6 and R3 but under estimated it at VT stage. The upslope and downslope yields obtained respectively in 2018 and 2017 were well simulated by the model but it overestimated the yield in 2018 for the downslope and underestimated it in 2017 for the upslope plots (Figure 3.17 b).

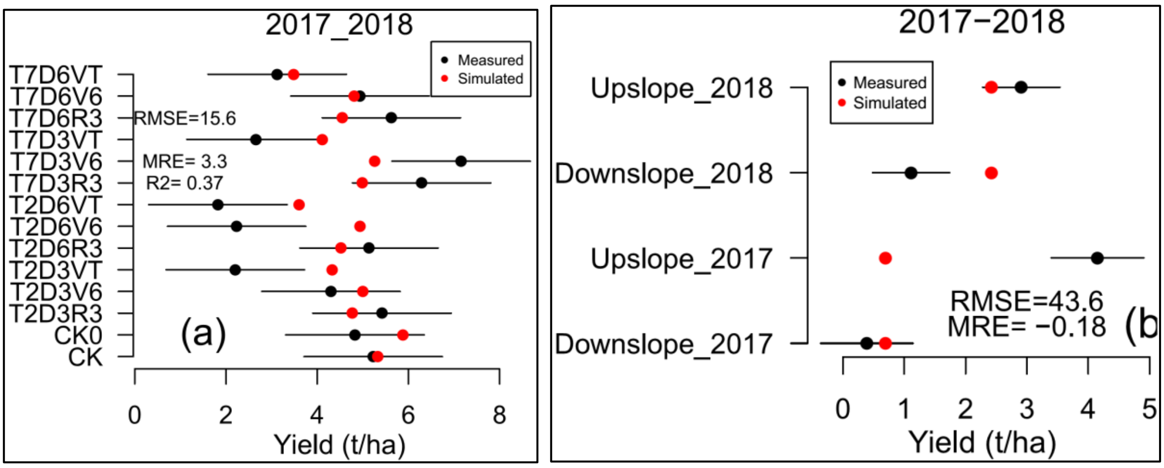


Figure 3.17. Yield simulations during the experiment in controlled (a) and uncontrolled (b) waterlogging conditions

3.3.3. Simulated excessive water indices and yield losses under waterlogging at different growth stages conditions

The test of correlation revealed a strong correlation between the observed grain yield losses and the indices (SSDI and SSEW) derived from EPIC model outputs, particularly when the waterlogging occurred at tasselling stage (R^2=0.8) (Figure 3.18).

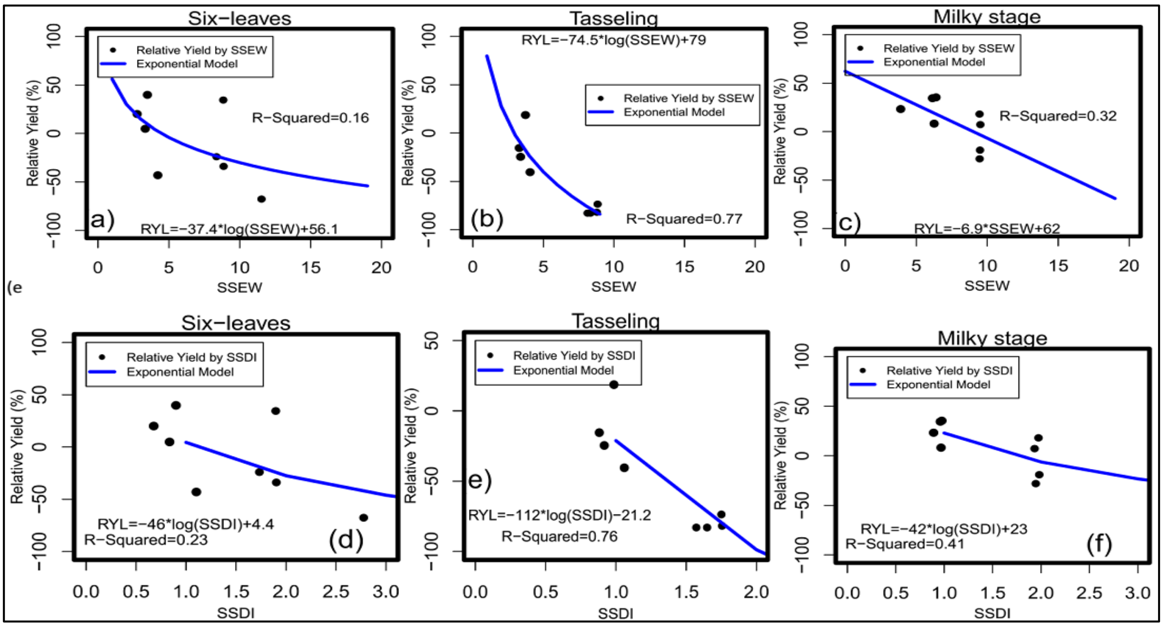


Figure 3.18. Relationship between Simulated exces water factot (SSEW), Simulated Stress Day Index (SSDI) and maize (Obatampa cultivar) yield loss in case of flooding at six-leave stage (a, d), at tasselling stage (b,e) at milky stage (c,f) during 2017/2018 at Boassa, Ouagadougou, Burkina Faso.

3.3.4. Concluding remarks

Under temporary waterlogging condition, the soil moisture simulated by the model was correlated to the water level fluctuation in the pipes. Under continuous flooding conditions, even if the model simulated some waterlogging periods with one-day as delay, it was able to reproduce the waterlogging periods that occurred during the crop growth cycle. EPIC model was able to simulate the LAI for all the treatments, except under long-term waterlogging conditions that occurred at downslope during 2017 and under anoxia condition at V6 and VT stages. At VT stage the effect on excessive soil moisture on the biomass is well simulated by the model, but it was not able to simulate the yield suppression effect that occurs at that stage. For R3 stage, the yield was well simulated but the model weakly simulated the effects of waterlogging on biomass at that stage. Indeed, the model overestimated the effects of excessive soil moisture on the final biomass when it occurs at the end of the crop cycle. Nevertheless, the effects of short-term flooding (≤3 days) due to 2-3 cm water level above the soil surface on biomass and yield were well simulated by the model when it occurs at V6 stage. Consequently, yield function based on the exponential regression between SSDI (or SSEW) and observed relative yield at VT stage can improved the grain yield simulation under anoxia and hypoxia conditions. This regression can also be used for yield loss assessment in this specific conditions. In natural conditions where the waterlogging periods started since the crop vegetative periods, the model simulated with high accuracy the cumulated effects of waterlogging on yield, but when most of the waterlogging periods occurs at the end of the season, the yield is not well estimated.

4. Discussion

4.1. Maize response to hypoxia and anoxia at different growth stages under field conditions

As the climate of the region is changing, excessive water stress induced by an increased amplitude and frequency of heavy rain events (Taylor et al., 2017; Salack et al., 2018) are becoming a challenge to rain-fed farming systems. In our first experiment, we tested the effects of excess and water stagnation on the growth, development and productivity of maize *Obatampa* cultivar with respect to 3 growth stages under ambient on-farm conditions. The state of waterlogging and stagnation was created by supplementary irrigation applied at the different growth stages, under some physical artifacts such as plastic tarpaulin and bund barriers to reduce surface and lateral advection and drainage. This on-farm experiments involving controlled waterlogging is unique in demonstrating that soil waterlogging is also a potential risk for West African maize cultivars in the context of extreme rainfall. During that experiment, we monitored soil waterlogging, stagnation depths (i.e. 2cm and 7cm) and duration (i.e. 3 days and 6 days) for 3 growth stages of maize. Many phenological aspects of *Obatampa* were negatively affected by soil waterlogging at V6 and VT stages. The reduction of maize height and lateness of the flowering stage similar to the results of Zugui et al. (2013) and Vwioko et al. (2017), were observed during the 2-year on-farm and controlled experiment, when 6 days of waterlogging occurred at V6 stage. Under prolonged waterlogging conditions, maize height decreased and the influence of waterlogging on plant height reduced with the postponement of timing and duration of the water stagnation. The significant delay in reaching the flowering stage was confirmed by the work of Zaidi et al. (2003). The important LAI and grain yield losses observed at VT stage after 3 and 6 days of flooding, contrasts with the results from Ren et al. (2014), who showed that the greater LAI reduction of 24% is observed when waterlogging occurs during the vegetative stages (V3 and V6). But, recently, based on yield parameters and chlorophyll content, Esteban and Solilap (2016), showed that tasselling stage was the most sensitive stage of white maize under seven day of waterlogging conditions. In addition, there is a potential recovering of *Obatampa* cultivar due nitrogen application after waterlogging stress as stated by other studies (e.g. Rao et al., 2002; Kaur et al., 2018; Manik et al., 2019). The biomass loss observed when waterlogging occurred during the six-leave vegetative stage (V6) is aligned with Tian et al. (2019), who found that the effect of waterlogging stress on the dry matter accumulation of maize is greatest at the V3 stage, followed by V6 and VT.

The rate of the yield loss was exponentially related to the stress day index (SDI). This result is similar to those reached by Kanwar et al. (1988), after a similar experimentation in the USA.

4.2. Maize response to cumulated waterlogging stress under field conditions

In the second experiment set-up in floodplain, we tested the cumulated effects of waterlogging, caused by rainfall and subsurface water flow, at different altitude across the landscape (upslope, middle slope and downslope), associated with water conservation techniques (with bunds or not) and two sowing dates of *Wang data* maize cultivar.

On flood plain conditions, where natural flooding occurs, location in downslope, follow by the presence of bunds are the main factors in the exposure to the soil waterlogging (Fu et al., 2000; Qin et al., 2013; Lim and Lee, 2017; Tang et al., 2018). In this context, the repetitive waterlogging can significantly affected maize growth parameters (height, LAI, number of leaves and biomass) and production when it occurs at vegetative stage. The biomass losses on downslope plots were estimated between 78% and 89% compared to the upslope plots. Considering the two experimental years, a grain yield losses on downslope plots represented 91% (in 2017) and 62% (in 2018). Indeed, early in the maize growth cycle, the root growth and respiration is directly and several times, influenced by the maladjustment of oxygen (O_2) in the rhizosphere in these conditions (Grable, 1966). Under oxygen deficit, the root becomes shorter and thicker and its ability of absorbing water and nutrient, decline significantly until the root death (Bramley et al., 2007; Zhang et al., 2009; Liu et al., 2013). Consequently, the plant suffers from stunting, decline in the root to shoot ratio, leave yellowing and the flower abscission (Najeeb et al., 2015). For Chen et al. (2014), the oxygen depletion in root zone, can decrease the chlorophyll synthesis and the activities of enzymes involved in this process. Finally, plant photosynthesis reduction leads to the growth inhibition or plant death. With the flooding time or frequency increasing, carboxylase activity gradually decreased, chlorophyll content decline, and senescence follow by loss of leaves (Maryam and Nasreen, 2012; Liu et al., 2013). Under the hypoxia condition, sensitive plants, such as maize, mainly get the energy for plant growth through the way of glycolysis, ethanol and lactic acid fermentation (Jiang and Zhang, 1999). In addition, the stability of cytoplasmic membrane of cells can also decline due to the natural synthesis of Malondialdehyde (MDA) ($CH_2 (CHO)_2$). This compound is capable to destroy the structure and function of biological membrane structure and reduced the cell metabolism (Hao et al., 2003; Liu et al., 2013).

Hence, in floodplain, a strategy that can help to escape all these effects, during vegetative phases, as early planting combining weather forecasting, may enhance the maize growth and productivity. Considering the strong exponential relationship (R^2=0.8) between SDI or SEW30 and maize (*Obatampa* and *Wang Data*) yield loss respectively under temporary and cumulated waterlogging conditions, non-structural adaptation measures such as crop insurance need to incorporate these indices (SDI and SEW30) for improving the protection against soil waterlogging, water stagnation and/or flooding. They can also be used in loss and damages assessment after flodding in agricultural sector. Evans et al. (1991), found that model based ond stress day index, predicted 69% of the maize relative yield variation in data pooled from four studies conducted in lysimeters in USA. In addition, these indices are used to predict yield under subsurface drainage in poorly drained sloping paddy fields (Jung et al., 2011) and serve as principle in the DRAINMOD model. A model used to simulate the hydrology of poorly drained, high water table soils on hourly or daily basis and to predict the effects of drainage and associated water management practices on water table depths, the soil water regime and crop yields (Skaggs, 2008). However, crop insurance systems in our region are covering the excessive rainfall and flooding risks by a traditional multi-peril crop insurance services which is often too expensive. So, other methods, such as the use of SDI or SEW30 indices against extreme rain events and flooding is a cheaper way to insure farmers against losses.

4.3. Simulation of maize productivity in waterlogging conditions

Field trial on maize response to hypoxia and anoxia at different growth stages under controlled field conditions provided the data which were used to calibrate the EPIC crop model. The data from the floodplain trial were useful in testing the performance of the crop model. The result showed that although, a 1-day delay observed sometimes between the simulated daily soil moisture saturation and observed waterlogging due to the internal daily water balance process, EPIC model simulates the waterlogging period under temporary flooding induced by irrigation and in natural flood plain conditions. The simulation of waterlogging periods under temporary flooding requiring the adjustment of the soil lateral hydraulic conductivity, confirms the improvement of soil moisture simulation in elevated soil moistures conditions by the variation of saturation hydraulic conductivity method (Doro. et al., 2017). In floodplain conditions, the parameterization of water table improving the simulation of waterlogging periods in this context is aligned with the fact that at lower slope positions, continuously subsurface water flow from surrounding fields can rise groundwater table into the shallow depths (Belder et al., 2005; Worou et al., 2012). Based on the good simulation of waterlogging periods, SSDI and SSEW from simulated soil moisture were highly correlated (R^2=0.8) with yield loss at the most sensitive growth stage *Obatampa* cultivar (the tasselling stage). This indices are aligned with

Shaw and Meyer, (2015), that pointed out the need to improve the empirical representation of plant responses to waterlogging for simulating crop yield.

Also, EPIC model simulated the LAI with accuracy when the hypoxia occurs at V6 (MRSE=74.6; 59.9) and R3 growth stage (MRSE=69.2; 56.9) and in case of anoxia at R3 stage (MRSE=69.2; 64.4). But the model underestimated the effects of hypoxia at VT, anoxia a V6 and VT and cumulative effects of waterlogging when it occurred since vegetative phase. Cavero et al. (2000) showed the tendency of the model to overestimate the LAI and biomass under extreme stress related to water. Indeed, flooded with 2-3cm of water level above the soil surface, the model simulated well the hypoxia effect on biomass, but overestimated the biomass under anoxia at V6 stage. When waterlogging occurred at R3 stages, the final biomass is underestimated by the model and it leads to the reduction of simulated biomass in case of waterlogging occurrence at post-flowering phase. In this context, although the underestimation of final biomass the model, the grain yield was well estimated for the *Obatampa* cultivar, but in case of *Wang Data,* it was overestimated. The sensitivity of *Obatampa* and *Wang Data* cultivars seems to vary with the growth stages where the waterlogging occurred, the timing and the duration of waterlogging. Under hypoxia and anoxia induced by 2-3cm of water level above the soil surface, the model overestimated the yield but with 7-8 cm of water level, its yield simulation was good. This divergence in the simulation is due to the difference of stress induced by the two type of water level applied. The excessive water stress induced by the 7-8 cm of water level was significantly less than the one due to 2-3cm (Figure 3.3). This result can be explained by the inability of our plot design, to handle water level induced by irrigation up to that level. There is few study on the efficiency of this experimental design for controlling waterlogging, but Barrett et al. (1986) pointed out a possible leakage of water alongside the barriers at the plot edges which can be accelerate which can be increased under high water level. This also affected the response at V6 stage. Besides, the good simulation of short-term flooding (≤3 days) effect on yield at V6 stage, the model overestimated the yield under temporary hypoxia. But, the yield estimation in floodplain frequently flooded from the vegetative stage to the end of the cycle was well simulated by the crop model. This inconsistency of in the response of the model under long-term excessive soil moisture, can be illustrated by its good performance under hydromorphic soils influenced by groundwater or waterlogging (Gaiser et al., 2010) and it is poor performance reported by Van der Velde et al. (2011) on the simulation of the negative impacts of excessive wet conditions, due to poor representations of critical factors affecting plant growth and management as such as the crop-specific root lodging processes and (ii) the underestimation of the impact of excessively wet soils on plant physiological and growth processes (through roots and root-mediated dynamics).

Our results confirmed that current EPIC crop models are limited for capturing the negative direct and indirect impacts crop of excessive soil moisture and heavy precipitation (Li et al., 2019), mostly when it occurred temporarily (i) at tasselling stage or exceeded 3 days at V6 stage or occurs continuously after the vegetative stage.

Based on our field trials, the needed improvements include better simulation of the different sensitivity of main crop growth to excessive soil moisture, yield suppression at the most sensitive crop phases and crop resilience after waterlogging period due to nitrogen application.

4.4. Potential limitations of ambient on-farm trials

During our trials, in 2017 and 2018, the plants at juvenile stage were attacked by fall-army worms (*Spodoptera frugiperda*). Therefore, different types of pesticides were applied to minimize the damages due to this pest and avoid its early resistance to a unique pesticide application. Also, in order to minimize any macro nutrient deficiency of the soil or that could be induced by the leaching through excessive water drainage, to reach optimal productivity and to focus our study on the oxygen deficiency effects during the two seasons, the fertilizers (NPK

23-10-5, urea and ammonium sulphate) were applied by the micro dose technic at different timing during the controlled and uncontrolled trials.

This fertilization as demonstrated by Kaur et al. (2018), caused the recovery of plants flooded at six-leave stage. In waterlogged soil, iron toxicity can induce nutritional disorders by its excessive absorption by the plant or by several nutrients’ adsorption (calcium, magnesium, potassium, phosphorus and iron itself). But instead of monitoring the iron toxicity in the soil by soil analysis, the degree of bronzing, susceptible to be due to this phenomenon, was monitored on maize plant. For the irrigation, diesel irrigation system used in 2017 then changed in 2018 into solar irrigation system, a better climate smart and efficient technology.

During our simulations, the soil moisture was not measured. In order to notice the soil waterlogging periods, the “pani pipes” were used to determine the waterlogging periods when they soil are submerged.

5. General Conclusion

During the 2017 and 2018 rainy seasons, first, we investigated the effects of soil waterlogging and water stagnation on *Obatampa* cultivar under ambient field conditions. The trials took place on a farm but artefact conditions were created to increase flooding potentials and reduced surface and sub-surface drainage. The experiments consisted of 42 randomized treatments including two controls, 3 repetitions of two water stagnation (1-3 days and 4-6 days), two water levels (2-3 cm and 7-8 cm levels above-surface) and three different phenological stages of maize *Obatampa*. The results showed that hypoxia (1-3 days of waterlogging) and anoxia (4-6 days of waterlogging), respectively reduced significantly the grain yield at tasselling stage. At six leave stage, only the anoxia significantly reduced the grain yield. Moreover, the grain yield loss decreases with the stress day index (SDI). Hence, SDI can be used to monitor temporarily maize field flooding under crop insurance scheme against excess water stress in the current context of climate change in the West African Sahel.

Second, we also investigated the cumulated effects of soil waterlogging and water stagnation on *Wang Data* cultivar under ambient field conditions. The trials took place on a farm under different topographical conditions (upslope, middle slope and downslope) and with the presence or absence of sand bunds which increase flooding. In addition the experiment included two sowing dates. The results showed that cumulated effect of frequent waterlogging when occurred from the vegetative stage to the end of crop cycle can drastically reduce growth and maize production. Under natural conditions, cumulative soil waterlogging, apart from the potential use of SEW30 for yield loss assessment in cumulative soil waterlogging adaptation measures such as early sowing (tested in 2018) combined with a seasonal forecasting can contributed to the reduction of damages induced by natural and uncontrolled flooding in the area prone to flooding in West African Sahel.

Third, EPIC model was able to simulate waterlogging period when it’s due to irrigation (controlled conditions) but also when it is caused by rainfall in downslope area (uncontrolled).

This performance allowed the generation of simulated stress day index (SSDI) and simulated stress day factor (SSEW) that can predict the yield failure when the flooding occurred at the most sensitive growth stage of the maize. At the opposite of empirical excessive water stress indices (SEW30 and SDI) which need a daily water level in the topsoil as input, SSEW and SSDI, based on soil moisture can facilitate the covering of yield loss by insurance systems since topsoil moisture can be estimated at large scale. These indices can also be used for improving the yield suppression that occurred at tasselling stage and which was not simulated by the model. Nevertheless, EPIC crop model was also able to capture the effects of the short-term waterlogging (≤3 days) at vegetative stage maize growth and production and cumulated effect of waterlogging on maize yield when the soil super saturation occurred frequently from early vegetative stage. Nevertheless, EPIC model need to be improved by including critical factors as such as the variation of critical aeration factor throughout its cycle and yield suppression which can be based on stress day index concept. EPIC crop model seems to not be suited for crop yield prediction under particularly "wet" climate change scenarios. Analytical and empirical approach seems to be relevant than crop modelling tools for yield loss prediction under waterlogging conditions.

Perspectives

The present study has shown that the yield loss of *Obatampa* and *Wang Data* cultivars can be predicted. The issue not considered, however, for the up scaling of these indices, especially the SDI or SSDI, is the variation of the crop susceptibility among maize cultivar. Evidence in literature suggests that this susceptibility to waterlogging can be specific to each cultivar or groups of cultivars. Therefore there is a need to extend the range of maize cultivar or staple food crop in West African Sahel which will be tested with the analytical assessment of loss and damages due to waterlogging.

As new tools in loss/damages assessment or crop insurance schemes, there is a need to test the analytical approach and new indices based on soil moisture in the framework of a crop insurance scheme at pilot stage

The Agricultural Model Inter-comparison and Improvement Project (AgMIP) protocols and pilot studies, Rosenzweig et al., (2013) pointed out the need of models well suited for crop production on high moisture soils and capable of simulating among others the cause–effect relationship between soil water condition, changes in climate, and their interaction with management factors. This study highlighted and open the way for an algorithm correction of EPIC model to account for the different sensitivity of crop growth stages to waterlogging by changing the source code.

References

Acuña T B, Dean G, Riffkin P.Constraints to achieving high potential yield of wheat in a temperate, high-rainfall environment in south-eastern Australia. *Crop Pasture Sci.,* 2011; 62: 125–136.

Ahmad R, Kanwar R S. Effect of Different Moisture Stress Levels on Corn Growth in Field Lysimeters. *Agricultural and Biosystems Engineering Publications*, 1991.

Aldana F, García P N, Fischer G. Effect of waterlogging stress on the growt, development and symptomatology of cape gooseberry (Physalis peruviana L.) plants. *Rev. Acad. Colomb. Cienc. Exactas Fís. Nat.,* 2014; 38: 393-400.

Alhassane A, Salack S, Ly M, Lona I, Traoré S B, Sarr B. Evolution des risques agroclimatiques associés aux tendances recentes du regime pluviométriqueen Afrique de l'Ouest soudano-sahelienne. *Sécheresse*, 2013; 24: 282-93.

Andrade C A, de Souza K R, de Oliveira Santos M, da Silva D M, Alves J D. Hydrogen peroxide promotes the tolerance of soybeans to waterlogging. *Sci. Hortic.,* 2018; 232: 40–45.

Asseng S, Keating B A, Huth N I, Eastham J. Simulation of perched water tables in a duplex soil Proceedings of MODSIM '97. *International Congress on Modelling and Simulation*, 1997.

Ayars J E, Evans R G. Subsurface drainage—What's next?. *Irrigation Drainage,* 2015; 64: 378-392.

Badu-Apraku B, Fakorede M A. *Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa.* Gewerbestrasse, Cham: Springer Nature, 2017.

Bange M P, Milroy S P, Thongba P. Growth and Yield of cotton in response to waterlogging. CSIRO Cotton Research Unit and the Australian Cotton Cooperative Research Centre. *Field Crops Research.,* 2004; 88 (2): 129-142.

Barrett C, Lennard E G, Leighton P D, Mcpharlin I R, Setter T, Greenway H. Methods to experimentally control waterlogging and measure soil oxygen in field trials. *Australian Journal of Soil Research,* 1986; 24 (4): 447-483.

Belder P, Spiertz J H, Bouman B A, Lu G, Tuong T P. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crops Res,* 2005; 93: 169-185.

Bennett J M, Roberton S D, Marchuk S, Woodhouse N P, Antille D L, Jensen T A. The soil structural cost of traffic from heavy machinery in Vertisols. *Soil Till. Res.,* 2019; 185: 85-93.

Bichet A, Diedhiou A. West African Sahel has become wetter during the last 30 years, but dry spells are shorter and more frequent. *Clim Res,* 2018; 75: 155-162.

Blein R, Soule B G, Dupaigre B F, Yerima B. Les potentialités agricoles de l'Afrique de l'Ouest (CEDEAO). Rapport d'étude, Fondation pour l'agriculture et la ruralité dans le monde, 2008; 1-116.

Bramley H, Turner D W, Tyerman S D, Turner N C. Water Flow in the Roots of Crop Species: The Influence of Root Structure, Aquaporin Activity, and Waterlogging. *Advances in Agronomy*, 2007; 133–196.

Cairns J E, Sonder K, Zaidi P H, Verhulst N, Mahuku G, Babu R, Nair S K, Das B, Govaerts B, Vinayan M T, Rashid Z, Noor J J, Devi P, San Vicente F, Prasanna B M. Maize Production in a Changing Climate: Impacts, Adaptation, and Mitigation Strategies. *Advances in Agronomy*, 2012; 1-114.

Calmon M A, Batchelor W D, Jones J W, Ritchie J T, Boote K J, Hammond L C. Simulating soybean root growth and soil water extraction using a function crop model. *Trans. ASAE,* 1999; 42: 1867-1877.

Cavero J, Farre I, Debaeke P, Faci J M. Simulation of Maize Yield under Water Stress with the EPICphase and CROPWAT Models. *Agronomy Journal,* 2000; 92 (4): 1-12.

Chen Y, Xi C, Hongjuan W, Yiqun B, Wei Z. Examination of the leaf proteome during flooding stress and the induction of programmed cell death in maize. *Proteome Sci.* 2014; 12 (33).

Coutinho I D, Henning L M, Döpp S A, Nepomuceno A, Moraes L A C., Marcolino-Gomes J. Flooded soybean metabolomic analysis reveals important primary and secondary metabolites involved in the hypoxia stress response and tolerance. *Environ. Exp. Bot.,* 2018; 153: 176-187.

Culati M L, Lenk A D, Jena S N. Root growth of groundnut (Arochis hypogaea L)as influenced by irrigation schedules under different water table conditions. *Indian Journal of Agricultural Science,* 2000; 70 (2): 122-124.

da Ponte N H T, Nunes Santos R I, Lima L, Filho W R, Lisboa Cunha R, Murad Magalhães M, Pinheiro H. Morphological assessments evidence that higher number of pneumatophores improves tolerance to longterm waterlogging in oil palm (Elaeis guineensis) seedlings. *Flora*, 2019; 250: 52-58.

Danso Issac. *Soil and water conservation technologies in the West African Sudan Savanna: Cropping system options to address variability of crop yield and impacts of climate change.* PhD thesis, University of Bonn, Bonn, Germany: Faculty of Agriculture , 2015; 1-135.

Dennis S, Dolferus R, Ellis M, Rahman M, Yu Y, Hoeren F U, Grover A, Ismond K P, Good A G, Peacock W J. Molecular strategies for improving water-logging tolerance inplants. *J. Exp. Bot.*, 2000; 51: 89-97.

Dhakad S, Ambawatia G, Verma G, Patel S, Rao K R, Verma S. Performance of Mole drain system for soybean (glycine max)-wheat (Triticum aestivum) cropping system of madhya pradesh. *Int. J. Curr. Microbiol. Appl. Sci.* 2018; 7: 2107–2112.

Di Baldassarre G, Montanari A, Lins H, Koutsoyiannis D, Brandimarte L, Blöschl G. Flood fatalities in Africa: From diagnosis to mitigation. *Geophys. Res. Lett.*, 2010; 37.

Doro L, Jones C, Williams J R, Norfleet M L, Izaurralde R C, Wang X, Jeong J. The Variable Saturation Hydraulic Conductivity Method for Improving Soil Water Content Simulation in EPIC and APEX Models. *Vadose Zone Journal* , 2017; 16 (3).

Duthion C. Effets d'une courte période d'excès d'eau sur la croissance et la production du maïs. *Agronomie*, 1982; 2 (2): 125-132.

Easterling W E, Aggarwal P K, Batima P, Brander K M, Erda L, Howden S M, Kirilenko A, Morton J, Soussana J-F, Schmidhuber J, Tubiello F N, *Food, fibre and forest products. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. Parry M L, Palutikof O F, Canziani J P, Van der Linden P J, Hanson C E, Eds. Cambridge, 2007.

Esteban J A, Solilap E L.Waterlogging: It's Effects on Different White Maize Genotypes. *International Journal of Sciences: Basic and Applied Research (IJSBAR),* 2016; 30 (1): 112-120.

Evans R O, Skaggs R W, Sneed R E. Stress day index models to predict corn and soybean relative yield under high water table conditions. *Trans. ASAE,* 1991; 34: 1997-2005.

FAO. *Disaster Risk Management Strategy in West Africa and the Sahel FAO 2011-2013.* Food and Agriculture Organization of the United Nations. Food and Agriculture Organization of the United Nations Eds. Rome, Italy., 2011.

FAO. *Review of ETo alculation methods and software.* Delobel Eds. Climate change and Bio-energy Unit (NRCB), 2009.

Fausey N, McDonald M. Emergence of inbred and hybrid corn following flooding. *Agron. J.* 1985; 77: 51–56.

Ferronato C, Marinari S, Francioso O, Bello D, Trasar-Cepeda C, Antisari L V. Effect of waterlogging on soil biochemical properties and organic matter quality in different salt marsh systems. *Geoderma*, 2019; 338: 302–312.

Filipovic V, Mallmann F J K, Coquet Y, Šimùnek J. Numerical simulation of water flow in tile and mole drainage systems. *Agric. Water Manag*., 2014; 146: 105–114.

Fosu-Mensah B Y. *Modelling maize (Zea mays L.) productivity and impact of climate change on yield and nutrient utilization in sub-humid Ghana.* Vlek P L G, Denich M, Martius C, Manschadi A, Bogardi J Eds. 2012.

Fu B, Chen L, Keming M, Huafeng W, Jun Z. The relationships between land use and soil conditions in the hilly area of the loess plateau in northern Shaanxi, China. *Catena,* 2000. 39: 69–78.

Gaiser T, de Barros I, Sereke I, Lange F. Validation and reliability of the EPIC model to simulate maize production in small-holder farming systems in tropical sub-humid West Africa and semi-arid Brazil. *Agriculture, Ecosystems and Environment*, doi: 10.1016/j.agee.2009.10.014, 2010; 135: 318–327.

Gerik T, Williams J, Dagitz S, Magre M, Meinardus A, Steglich E, Taylor R. *Environmental Policy Integrated Cimate Model - User's Manual Version 0810.* Texas A&M

AgriLife Eds. East Blackland Road, Temple: Blackland Research and Extension Center, 2015.

Giannini A, Salack S, Lodoun T, Ali A, Gaye A T, Ndiaye O. Unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environ. Res. Lett.*, 2013; 8.

Gibson G. *Utilising Innovative Management Techniques to Reduce Waterlogging.* 2014.

Gill M B, Zeng F, Shabala L, Böhm J, Zhang G, Zhou M, Shabala S. The ability to regulate voltage-gated K+-permeable channels in the mature root epidermis is essential for waterlogging tolerance in barley.» *J. Exp. Bot.*, 2018: 667–680.

Glinski J. Soil Physical Conditions and Plant Roots. *Boca Raton FL: CRC Press*, 2018.

Grable A R. *Soil aeration and plant growth.* 1966; 18: 1-123.

Greenway H, Armstrong W, Colmer T D. Conditions leading to high CO_2 (> 5 kPa) in waterlogged–flooded soils and possible effects on root growth and metabolism.» *Ann. Bot.*, 2006; 98: 9-32.

Guan K, Sultan B, Biasutti M, Baron C, Lobell D B. What aspects of future rainfall changes matter for crop yields in West Africa? *Geophys Res Lett.*, 2015; 42: 8001-8010.

Guenette K G, Hernandez-Ramirez G. Tracking the influence of controlled traffic regimes on field scale soil variability and geospatial modeling techniques. *Geoderma* 2018; 328: 66–78.

Habibzadeh F, Sorooshzadeh A, Pirdashti H, Sanavy S. Effect of nitrogen compounds and tricyclazole on some biochemical and morphological haracteristics of waterlogged-canola. *Int. Res. J. Appl. Basic Sci.* 2012; 3: 77-84.

Han M, Zhao C, Šimůnek J, Feng G. Evaluating the impact of groundwater on cotton growth and root zone water balance using Hydrus-1D coupled with a crop growth model. *Agricultural Water Management*, 2015; 160: 64-75.

Hao Y L, Pan J B, Zhang Q Z, Yang J. Effect of Waterlogging on Growth and Generation at Different Stages in Maize. *Chinese Agricultural Science Bulletin*, 2003; 19 (6): 58-63.

Hardjoamidjojo S, Skaggs R W, Schwab G O. Corn yield response to excessive soil water conditions. *TRANSACTIONS of the ASAE*, 1982; 4 (25): 922-927.

Huang X, Fan Y, Shabala L, Rengel Z, Shabala S, Zhou M. A major QTL controlling the tolerance to manganese toxicity in barley (Hordeum vulgare L.). *Mol. Breed*, 2018; 38 (16): 12-43.

IPCC. *Climate Change:The Physical Science Basis.In Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Qin D, Plattner G K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V, Midgley P M, Stocker T F Eds. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013.

IRI. *Index insurance for Ethiopian farmers.*New York: International Research Institute for Climate and Society (IRI), 2008.

Jackson M, Ricard B. Physiology, Biochemistry and Molecular Biology of Plant Root Systems Subjected to Flooding of the Soil, in Root Ecology. *Springer*, 2003: 193–213.

Jaiswal A, Srivastava J. Changes in reactive oxygen scavenging systems and protein profiles in maize roots in response to nitric oxide under waterlogging stress. *Indian J. Biochem. Biophys.*, 2018; 55: 26-33.

Jiang H W, Zhang Z X. Anaerobic metabolism and flooding tolerance in maize. *Journal of Hubei Agricultural College*, 1999; 19 (1): 79-84.

Jones C A, Dyke P T, Williams J R, Kiniry J R, Benson V W, Griggs R H. EPIC: an operational model for evaluation of agricultural sustainability. *Agric. Syst.*, 1991; 37: 341-350.

Jones J W, Antle J M, Basso B, Boote K J, Contant R T, Foster I, Godfray H C, Herrero M, Howitt R E, Janssen S, Keaing B A, Munoz-Carpena R, Porter C H, Rosenzweig C, Wheeler T R. Toward a new generation of agricultural system data, models, and knowledge products : state of agriculture systems science. *Agric. Syst.*, 2016; 155: 269–288.

Jung K, Eul-Su Y, Chang-Yeong P, Jae-Bok H, Young-Dae C, Ki D P. Stress Day Index to Predict Soybean Yield Response by Subsurface Drainage in Poorly Drained Sloping Paddy Fields. *Korean Journal of Soil Science and Fertilizer*, 2011; 44, 5: 702-708.

Kanwar R S, Baker J L, Mukhtar S. Excessive Soil Water Effects at Various Stages of Development on the Growth and Yield of Corn. *Transactions of the ASAE,* 1998: 34 (5): 1991-1996.

Kanwar Rameshwar S. Stress-Day Factor and Stress-Day Index as Indicators of Drainage Needs of Soils. *Transactions of the ASAE*, 1988; 31: 1423–1429.

Kaur G, Zurweller B, Motavalli P P, Nelson K A. Screening Corn Hybrids for Soil Waterlogging Tolerance at an Early Growth Stage. *Agriculture*, 2019; 9 (2): 1-28.

Kaur G, Nelson K, Motavalli P. Early-Season Soil Waterlogging and N Fertilizer Sources Impacts on Corn N Uptake and Apparent N Recovery Efficiency. *Agronomy*, 2018; 8 (7).

Keating B A, Robertson M J, Muchow R C, Huth N I. Modelling sugarcane production systems. Development and performance of the sugarcane module. *Field Crops Res.,* 1999; 61: 253–271.

Kijne J W. Abiotic stress and water scarcity: identifying and resolving conflicts from plant level to global level. *Field Crops Res.*, 2006; 97: 3–18.

Laanbroek H. Bacterial cycling of minerals that affect plant growth in waterlogged soils: a review. *Aquat. Bot.*, 1990; 38: 109-125.

Lavigne D, Boucher L, Vidal L. Les bas-fonds en Afrique tropicale humide : stratégies paysannes, contraintes agronomiques et aménagements.Pichot Eds. In *Fertilité du milieu et stratégies paysannes sous les tropiques humides, actes du séminaire international, CIRAD*, 1996: 148-161.

Lawson Zankli Namo. *Thresholds for operational agro-climatic monitoring and early warning against high impact rainfall events in the Sudan-Sahel region, West Africa.* Master Research Program in Climate Change and Human Security, University of Lome, Lomé: Climate Change and Human Security, 2018.

Lebel T., Ali A. Recent trends in the central and western Sahel rainfall regime (1990–2007). *J. Hydrol.,* 2009; 375 (1–2): 52–64.

Leblois A, Quirion P, Alhassane A, Traoré S. Weather Index Drought Insurance: An Ex Ante Evaluation for Millet Growers in Niger. *Environ Resource Econ*, 2014; 57: 527–551.

Lerch R N, Lin C H, Goyne K W, Kremer R J, Anderson S H. Vegetative buffer strips for reducing herbicide transport in runoff: effects of buffer width, vegetation and season. *J. Am. Water Resour. Assoc.*, 2017; 53: 667–683.

Li W, Mo W, Ashraf U, Li G, Wen T, Abrar M, Gao L, Liu J, Hu J. Evaluation of physiological indices of waterlogging tolerance of different maize varieties in South China. *Applied Ecology and Environmental Research,* 2018; 16 (2): 2059-2072.

Li X Y, Liu Z Y, Li T X. An impact test study of the flood disasters on summer corn's characters and yield. *Acta Meteorol. Sin*, 2011; 31: 79-82.

Li Y, Guan K, Schnitkey G D, DeLucia E, Peng B. Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*, 2019.

Lim J, Kyoo-seock L. Investigating flood susceptible areas in inaccessible regions using remote sensing and geographic information systems. *Environ Monit Assess*, 2017: 189 - 196.

Liu A, Jian-qiang Z, Tao J. Advance of the Research on Crop Suffering from Waterlogged Stress. *Third International Conference on Intelligent System Design and Engineering Applications.*, doi:10.1109/ISDEA.2012.59, 2013

Liu, H S, Meng F T, Yang Q H, Han J F, Wang C L, Dun W T. Effect of waterlogging on the growth and anti-oxidative enzyme activity of sesame root system. *Plant Physiology Communications,* 2005; 41(1): 45-47.

Liu Y Z, Tang B, Zheng Y L, Ma K J, Xu S Z, Qiu F Z. Screening methods for waterlogging tolerance at maize (*Zea mays* L.) seedling stage. *Agric.Sci.China,* 2010; 9 (3): 362-369.

Lizaso J I, Ritchie, J T. Maize shoot and root response to root zone saturation during vegetative growth. *Agron. J.*, 1997; 89: 125-134.

Luan H, Guo B, Pan Y, Lv C, Shen H, Xu R. Morpho-anatomical and physiological responses to waterlogging stress in different barley (Hordeum vulgare L.) genotypes. *Plant Growth Regulation,* 2018; 85 : 399–409.

Lubkowski K, Grzmil B. Controlled release fertilizers.» *Pol. J.Chem. Technol.,* 2007; 9: 83–84.

Ly M, Traore S B, Alhassane A, Sarr, B. Evolution of some observed climate extremes in the West African Sahel. *Weather and Climate Extremes*, 2013; 1: 19-25.

Maidment R I, Allan R P, Black E. Recent observed and simulated changes in precipitation over Africa. *Geophys. Res. Lett.*, 2015; 42: 1–10.

Manik S M N, Pengylley G, Dean G, Field B, Shabala S, Zhou M. Soil and crop management practices to minimize the impact f waterlogging on crop productivity. *Front. Plant Sci.*, 2019; 10 (140): 1-23.

Maryam A, Nasreen S. A Review: Water Logging Effects on Morphological, Anatomical, Physiological and Biochemical Attributes of Food and Cash crops. *International Journal of Water Ressources and Environmental Sciences,* 2012; 1 (4): 113-120.

Mathon V, Laurent H, Lebel T. Mesoscale convective system rainfall in the Sahel. *J. Appl. Meteor*., 2002; 41: 1081-1092.

McCaskill M, Kearney G. Control of water leakage from below the root zone by summer-active pastures is associated with persistence, density and deep rootedness. *Crop Pasture Sci.,* 2016; 67: 679–693.

McDaniel B K, Binder, B M. Ethylene receptor1 (ETR1) is sufficient and has the predominant role in mediating inhibition of ethylene responses by silver in Arabidopsis thaliana. *J. Biol. Chem.*, 2012; 112 (383034).

McKight P E, Najab J. *Kruskal-Wallis Test.* Weiner I B, Craighead W. E Eds. The Corsini Encyclopedia of Psychology, 2010.

Meyer W S, Godwin D C, White R J B. SWAGMAN®Destiny: A tool to predict productivity change due to salinity, waterlogging and irrigation management.» Édité par Australian Society of Agronomy. *In 'Proceedings of the 8th Australian Agronomy Conference'.* Toowomba,: The Regional Institute, 1996: 425–428.

Milroy S P, Bange M P, Thongbai P. Cotton leaf nutrient concentrations in response to waterlogging under field conditions. *Field Crops research,* 2009; 113 (3): 246-255.

Morales-Olmedo M, Ortiz M, Sellés G. Effects of transient soil waterlogging and its importance for rootstock selection. *Chilean J. Agric. Res.*, 2015; 75: 45–56.

Mtongori H I, Stordal F, Benestad R E, Mourice S K, Pereira-Floress M E, Justino F. Impacts of climate and farming management on maize yield in southern Tanzania. *African Crop Science Journal,* 2015; 23 (4): 399-417.

Mukhtar S, Baker J L, Kanwar R S. Corn growth as affected by excess soil water. *Trans. Amer. Soc. Agr. Eng,* 1990; 33: 437-442.

Muller B, Leblois A. *Aléas, développement et assurances agricoles.* Eds Les Sociétes. 2013.

Muñoz-Carpena R, Fox G A, Ritter A, Perez-Ovilla O, Rodea-Palomares I. Effect of vegetative filter strip pesticide residue degradation assumptions for environmental exposure assessments. *Sci. Total Environ.* 2018; 619: 977–987.

Najeeb U, Bange M P, Tan D K, Atwell B J. Consequences of waterlogging in cotton and opportunities for mitigation of yield losses. *AoB PLANTS*, 2015; 7 (plv080).

Najeeb U, Tan D K, Bange M P, Atwell B J. Protecting cotton crops under elevated CO_2 from waterlogging by managing ethylene. *Funct. Plant Biol.*, 2018; 45:340–349.

Najeeb U, Tan D K, Bange M P, Atwell B J. *Stress-induced fruitStress-induced fruit abscission in cotton and role of ethylene*, 45, In *Proceedings of the 18th Australian Agronomy Conference,* 1-4. Ballarat VIC: Australian Society of Agronomy, 2017.

Nguyen L T, Osanai Y, Anderson I C, Bange M P, Tissue D T, Singh B K. Flooding and prolonged drought have differential legacy impacts on soil nitrogen cycling, microbial communities and plant productivity. *Plant Soil*, 2018; 431: 371-387.

Nichols P. *Yanco Subterranean Clover. Orange: Department of Primary Industries and Regional Development (DPIRD).* 2018.

Nicholson S E. On the question of the“recovery”of the rains in the West African Sahel. *J. Arid Environ.*, 2005; 63: 615–641.

Nielsen R L. *Effects of Flooding or Ponding on Corn prior to Tasseling.* 2019. https://www.agry.purdue.edu/ext/corn/news/timeless/pondingyoungcorn.html (visited the 17/10 /2019).

Olsson L, Eklundh L, Ardö J. A recent greening of the Sahel—trends, patterns and potential causes. *Journal of Arid Environments,* 2005; 63 (3): 556–566.

Otie V, Ping A, Udo I, Eneji E. Brassinolide effects on maize (*Zea mays* L.) growth and yield under waterlogged conditions. *Journal of Plant Nutrition,* 2019; 42 (8): 1-16.

Palla A, Colli M, Candela A, Aronica G, Lanza L. Pluvial flooding in urban areas: the role of surface drainage efficiency. *Flood Risk Manag*, 2018: 663–676.

Pang J Y, Newman I, Mendham N, Zhou M, Shabala S. Microelectrode ion and O2 fluxes measurements reveal differential sensitivity of barley root tissues to hypoxia. *Plant Cell Environ.* 2006; 29: 1107–1121.

Panozzo A, Dal Cortivo C, Ferrari M, Vicelli B, Varotto S, Vamerali T. «Morphological Changes and Expressions of AOX1A, CYP81D8, and Putative PFP Genes in a Large Set of Commercial Maize Hybrids Under Extreme Waterlogging.» *Frontiers in Plant Science,* 2019; 10 (62): 1-14.

Panthou G, Vischel T, Lebel T. Recent trends in the regime of extreme rainfall inthe Central Sahel. *Int. J. Climatol.*, 2014; 34: 3998 – 4006.

Pereira E I, Nogueira A A R, Cruz C C, Guimaraies G G, Foschini M M, Bernardi A C, Ribeiro C. «Controlled Urea Release Employing Nanocomposites Increases the Efficiency of Nitrogen Use by Forage.» *ACS Sustainable Chemistry & Engineering,* 2017.

Ploschuk R A, Miralles D J, Colmer T D, Ploschuk E L, Striker G G. Waterlogging of winter crops at early and late stages: impacts on leaf physiology, growth and yield. *Front. Plant Sci,* 2018; 9 (1863): 1-12.

Prathapar S, Rajmohan N, Sharma B, Aggarwal P. Vertical drains to minimize duration of seasonal waterlogging in Eastern Ganges Basin flood plains. a field experiment. *Nat. Hazards,* 2018; 92: 1-17.

Prithwiraj D. «Smart water management in rice by IRRI’S cost effective pani-pipe method for sustainable and climatesmart rice development – A short communication. International Journal of Agriculture, *International Journal of Agriculture,* 2017; 9 (17) : 4154-4155.

Pujol V, Wissuwa M. Contrasting development of lysigenous erenchyma in two rice genotypes under phosphorus deficiency. *BMC Res. Notes*, 2018.

Qian L, Wang X G, Luo W B, Qi Z M, Sun H W, Luo Y Y. An improved CROPR model for estimating cotton yield under soil aeration stress. *Crop Past. Sci.,* 2017; 68: 366–377.

Qin H, Li Z, Fu G. The effects of low impact development on urban flooding under different rainfall characteristics. *Journal of Environmental Management*, 2013; 129: 577–585.

Rao R, Li Y C. Management of flooding effects on growth of vegetable and selected field crops. *Hortic. Technol*, 2003: 610-616.

Rao R, Li Y, Bryan H H, Reed S T, D'ambrosio F. *Assessment of foliar sprays to alleviate flooding injury in corn (Zea mays L.).* Lake Alfred Eds, Florida State Horticultural Society. Proceedings of the Florida State Horticultural Society. Lake Alfred, Florida State: Horticultural Society, 2002.

Ravelo C J, Reddell D L, Hiler E A, Skaggs R W. Incorporating crop needs into drainage system design. *Transactions of the ASAE,* 1982; 25 (3): 623-629.

Ren B, Zhang J, Dong S, Liu P, Zhao B. Responses of carbon metabolism and antioxidant system of summer maize to waterlogging at different stages. *Journal of Agronomy and Crop Science,* 2018: 1-10.

Ren B, Zhang J, Dong S, Liu P, Zhao B. Effects of Waterlogging on Leaf Mesophyll Cell Ultrastructure and Photosynthetic Characteristics of Summer Maize.» *PLoS ONE*, 2016; 11 (9):1-12.

Ren, Baizhao, Jiwang Zhang, Xia Li, Dong, Shuting Fan Xia, Peng Liu, et Bin Zhao. «Effects of waterlogging on the yield and growth of summer maize under field conditions.» *Can. J. PLant. Sci*, n° 94 (2014): 23-31.

Ritzema H, Satyanarayana T, Raman S, Boonstra J. Su-surface drainage to combat waterlogging and salinity in irrigated lands in India: lessons learned in farmers' fields. *Agric. Water Manag.* 2008; 95: 179–189.

Rochester I, Peoples M, Hulugalle N, Gault R, Constable G. Using legumes to enhance nitrogen fertility and improve soil condition in cotton cropping systems. *Field Crops Res.,* 2001; 70: 27-41.

Roloff G, de Jong R, Zentner R P, Campbell C A, Benson V W. Estimating spring wheat yield variability with EPIC. *Can. J. Soil. Sci.,* 1998; 78: 541–549.

Roper M. M., Davies S L, Blackwell P S, Hall D J M, Bakker D M, Jongepier R, Ward P R. Management options for water-repellent soils in Australian dryland agriculture. *Soil Res.*, doi: 10.1071/SR14330, 2015; 53: 786–806.

Rosenzweig C, Tibiello F N, Goldberg R, Mills E, Bloomfield J. Increased crop damage in the US from excess precipitation under climate change. *Global Environ. Change*, 2002; 12: 197-202.

Rosenzweig C, Jones J W, Hatfield J L, Ruane A C, Boote K J, Thorburn P, Antle J M, Nelson G C, Porter C, Janssen S, Asseng S, Basso B, Ewert F, Wallach D, Baigorria G, Winter J M. «The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies.» *Agric. Forest Meteorol.*, 2013; 170: 166-182.

Rosenzweig C, Iglesias A, Yang X B, Epstein P, Chivian E. Climate change and extreme weather events Implications for food production, plant diseases, and pests. *Global Change & Human Health*, 2001; 2 (2): 90-91.

Salack S, Sarr B, Sangare S K, Ly M, Sanda I S, Kunstmann H. Crop−climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa. *CLIMATE RESEARCH Clim Res.* Contribution to CR Special 31 'Modelling climate change impacts for food security, 2015; 65: 107–121.

Salack S, Giannini A, Diakhaté M, Gaye A T, Muller B. Oceanic influence on the subseasonal to interannual timing and frequency of extreme dry spells over the West African Sahel. *Clim. Dynam.*, 2014; 42: 189–201.

Salack S, Klein C, Giannini A, Sarr B, Worou O N, Belko N, Bliefernicht J, Kunstman H. Global warming induced hybrid rainy seasons in the Sahel.» *Environmental Research Letters*, 2016; 11 (10): 1-11.

Salack S, Saley I A, Lawson-Zankli N, Zabre I, Daku, E K. Scales for rating heavy rainfall events in the West African Sahel. *Weather and climate extremes*, 2018; 21: 36-42.

Sanfo S, Barbier B, Dabiré I W P, Vlek P L G, Fonta W M, Ibrahim B, Barry B. Rainfall variability adaptation strategies: An ex-ante assessment of supplemental irrigation from farm ponds in southern Burkina Faso. *Agricultural Systems*, 2017; 152: 80-89.

Sarkar A, Banik M, Ray R, Patra S. Soil moisture and groundwater dynamics under biodrainage vegetation in a waterlogged land. *Int. J. Pure Appl. Biosci.* 2018; 6: 1225–1233.

Sarr B, Atta S, Kafando L. Revue des indices climatiques utilisées dans les systèmes d'assurances agricoles indicielles en Afrique. *Secheresse,* 2012; 23: 255-260.

Sarr B. Present and future climate change in West Africa: a crucial input for agricultural research prioritization for the region.» *Atmospheric Sciences*, 2011; 13: 108–112.

Sarr B, Atta S, Ly M, Salack S, Ourback T, Subsol S, George D A. «Adapting to climate variability and change in smallholder farming communities: a case study from Burkina Faso, Chad and Niger (CVCADAPT).» *J. Agric. Ext. Rural Dev.*, 2015; 7 (1).

Savvides A, Ali S, Tester M, Fotopoulos V. Chemical priming of plants against multiple abiotic stresses: mission possible? *Trends Plant Sci.*, 2016; 21: 329 – 340.

Shabala S. Physiological and cellular aspects of phytotoxicity tolerance in plants: the role of membrane transporters and implications for crop breeding for waterlogging tolerance. *N. Phytol.*, 2011;190: 289-298.

Sharma S K, Kulshreshtha N, Kumar A, Yaduvanshi N P S, Singh M, Prasad K R K, Basak N, Waterlogging effects on elemental composition of wheat genotypes in sodic soils.» *J. Plant Nutr.*, 2018; 41: 1252 - 1262.

Shaw R E, Meyer W S, McNeill A.,Tyerman S D. Waterlogging in Australian agricultural landscapes:a review of plant responses and crop models. *CSIRO PUBLISHING. Crop & Pasture Science,* 2013; 64: 549–562.

Shaw R E, Meyer W S. Improved Empirical Representation of Plant Responses to Waterlogging for Simulating Crop Yield. *Crop Ecology & Physiology*, 2015; 107 (5): 1711-1723.

Singh G, Lal K. Review and case studies on biodrainage: An alternative drainage system to manage waterlogging and salinity. *Irrigation Drainage,* 2018; 67: 51–64.

Sipalla T A, Sipalla F. *DT Maize, A Quarterly Bulletin of the Drought Tolerant Maize for Africa Project.* International Maize and Wheat Improvement Center Eds. Nairobi, 2013.

Skaggs R W. DRAINMOD: A simulation model for shallow water table soils. *In 'South Carolina Water Resources Conference.* Clemson: Clemson University Restoration Institute, 2008.

Smale M, Byerlee D, Jayne T. *Maize Revolutions in Sub-Saharan Africa.* An African Green Revolution. Springer,. Otsuka K., Larson D. Dordrecht Eds, 2013.

Steduto P, Hsiao T C, Raes D, Fereres E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal* 101 (2009): 426-437.

Sultan B, Janicot S. The West African monsoon dynamics. Part II: the‘‘preonset” and‘‘onset”of the summer monsoon. *J. Clim.,* 2003; 16: 3407–3427.

Sundgren T K, Uhlen A K, Lillemo M, Briese C, Wojciechowski T. Rapid seedling establishment and a narrow root stele promotes watrerlogging tolerance in spring wheat. *J. Plant Physiol.* 2018; 227: 45-55.

Sylla M B, Giorgi F, Pal J S, Gibba P, Kebe I, Nikiema M. Projected Changes in the Annual Cycle of High-Intensity Precipitation Events over West Africa for the Late Twenty-First Century. *Journal of Climate,* 2015; 28 (16): 6475-6488.

Ta, S., K.Y. Kouadio, K. Ali, E. Toualy, A. Aman, et F. Yoroba. «West Africa extreme rainfall events and large-scale ocean surface and atmospheric conditions in the tropical Atlantic.» *Advances in Meteorology* 1940456 (2016): 1-14.

Tang X, Shu Y, Lian Y, Zhao Y, Fu Y. A spatial assessment of urban waterlogging risk based on a Weighted Naïve Bayes classifier. *Science of the Total Environment*, 2018. 630: 264–274.

Taylor C M, Belusic D, Guichard F, Parker D J, Vischel T, Bock O, Harris P P, Janicot S, Klein C, Panthou G. «Frequency of extreme Sahelian storms tripled since 1982 in satellite observations.» *Nature*, 2017; 544: 475-488.

Teixeira D L, de Matos A T, de Matos M P, Miranda S T, Vieira D P. Evaluation of the effects of drainage and different rest periods as techniques for unclogging the porous medium in horizontal subsurface flow constructed wetlands. *Ecol. Eng.,* 2018; *1*20: 104 –108.

Tewari S, Mishra A. Flooding Stress in Plants and Approaches to Overcome Plant Metabolites and Regulation Under Environmental Stress. *Elsevier*, 2018: 355–366.

Tian L, Li J, Bi W, Zuo S, Li L, Li W, Sun L. Effects of waterlogging stress at different growth stages on the photosynthetic characteristics and grain yield of spring maize (Zea mays L.) Under field conditions. *Agricultural Water Management*, 2019; 218: 250-258.

Trenkel M E. *Slow-and Controlled-Release and Stabilized Fertilizers: An Option for Enhancing Nutrient Use Efficiency in Agriculture.* Paris: Internationalfertilizer industry association., 2010.

Tuohy P, O'Loughlin J, Fenton O. Modeling performance of a tile drainage system incorporating mole drainage. *Trans. ASABE,* 2018; 61: 169–178.

Van der Velde M, Tubiello F N, Vrieling A, Bouraoui F. Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data. *Climatic Change,* 2011; 113 (3-4): 751–765.

Vizy E K, Cook K H. Mid-Twenty-First-Century Changes in Extreme Events over Northern and Tropical Africa. *Journal of Climate,* 2012; 25 (17): 5748-5767.

VOTO. *A COMPLETE CURRICULUM AND GUIDE TO MAIZE PRODUCTION IN GHANA.* 2015.

Vwioko E, Adinkwu O, El-Esawi M A. Comparative physiological biochemical, and genetic responses to prolonged waterlogging stress in okra and maize given exogenous ethylene priming. *Front. Physiol,* 2017; 8 (632): 1-13

Vwioko E, Adinkwu O, El-Esawi, M A. Comparative Physiological, Biochemical, and Genetic Responses to Prolonged Waterlogging Stress in Okra and Maize Given Exogenous Ethylene Priming. *Front Physiol.,* 2017; 8 (632): 1-18.

Wang X, He X, Williams J R, Izaurralde R C, Atwood J D. Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. *Trans. ASAE,* 2005; 3 (48): 1041–1054.

Wang X, Deng Z, Zhang W, Meng Z, Chang X, Lv M. Effect of Waterlogging Duration at Different Growth Stages on the Growth, Yield and Quality of Cotton. *PLoSONE,* 2017; 12 (1).

Wani S H, Choudhary M, Kumar P, Akram A N, Surekha C, Ahmad P. *Marker-assisted breeding for abiotic stress tolerance in crop plants.* Gosal and Wani. Cham: Biotechnologies of Crop Improvement Eds, 2018.

Warren J M, Hanson P J, Iversen C M, Kumar J, Walker A P, Wullschleger S D. Root structural and functional dynamics in terrestrial biosphere models -evaluation and recommendations. *New Phytol*, 2015; 205: 59–78.

Williams J R, Jones C A, Dyke P T. A modeling approach to determining the relationship between erosion and soil productivity. *Trans Am Soc Agnc Eng*, 1984; 27: 129-144.

Williams J R, Izaurralde R C. *The APEX Model.* 2009.

Williams J R. *The EPIC model. Computer Models of Watershed Hydrology.* Water Resources Publications. Water Resources Publications Eds. Highlands Ranch, CO: Singh, V.P., 1995.

Wollmer A C, Pitann B, Mühling K H. Nutrients deficiency do not contribute to yield loss after waterlogging events in winter wheat (Triticum aestivum). *Ann. Appl. Biol.*, 2018; 173: 141–153.

World Bank. *Africa development indicators 2017.* World Bank Eds. Washington DC, 2007.

World Bank —. *Inondations du 1er Septembre 2009 au Burkina Faso. Evaluation des dommages, pertes et besoins de construction, de reconstruction et de relèvement (French).* Washington, DC, 2010.

World Reference Base for Soil Resources WRB. *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps.* Rome: FAO, 2015.

Worou O N, Gaiser T, Saito K, Goldbach H, Ewert F. Simulation of soil water dynamics and rice crop growth as affected by bunding and fertilizer application in inland valley systems of West Africa. *Agriculture, Ecosystems and Environment*, 2012; 162: 24-35.

Wu H, Xiang J, Chen H, Zhang Y, Zhang Y, Zhu F. Effects of exogenous growth regulators on plant elongation and carbohydrate consumption of rice seedlings under submergence. *J. Appl. Ecol.*, 2018; 29: 149–157.

Yamauchi T, Colmer T D, Pedersen O, Nakazono M. Regulation of root traits for internal aeration and tolerance to soil waterlogging-flooding stress. *Plant Physiol.,* 2018; 176: 1118-1130.

Yang H, Huang T, Ding M, Lu D, Lu W. Effects of Waterlogging Around Flowering Stage on the Grain Yield and Eating Properties of Fresh Waxy Maize. *Cereal Chem,* 2016; 93 (6): 605-611.

Zahiri E P I, Bamba A M, Famien A K, Koffi A, Ochou D. A mesoscale extreme rainfall events in West Africa: the cases of Niamey (Niger) and the upper Ouémé valley (Benin). *Weather and Climate Extremes,* 2016; 13: 15–34.

Zaidi P H , Ralique S, Singh N N. Response of maize genotypes 10 excess moisture stress: morphophysiological effects and basis of tolerance. *Eur. J. Agron.*, 2003; 19: 383-399.

Zhang E R, Ren Y Y, Hu H Q. Effect of calcium on growth and respiratory metabolism of pepper seedlings root under flood stress. *Acta Horticulturae Sinica,* 2009; 36 (12): 1749-1754.

Zhou J, Cheng G, Li X, Hu B X, Wang G. Numerical Modeling of Wheat Irrigation using Coupled HYDRUS and WOFOST Models. *Soil Science Society of America Journal,* 2012; 76 (2).

Zhu J Q, Ou G H, Liu W Y, Zang D F. Influence of subsurface waterlogging followed by surface waterlogging on yield and quality of cotton. *Scientia Agricutura Sinica*, 2003; 36 (9): 1050-1056.

Zhu J Q, Cheng L G, Wu L R, Liu W. Experimental study on rape suffering from continuous subsurface waterlogging. *Transactions of the Chinese Society of Agricultural Engeneering*, 2005; Z1: 63-67.

Zougmoré R, Jalloh A, Tioro A. Climate-smart soil water and nutrient management options in semiarid West Africa:a review of evidence and analysis of stone bunds and zaï techniques. *Agriculture & Food Security,* 2014; 3 (16).

Zugui L, Zhandong L, Junfu X, Jiqin N, Wenjun G. Waterlogging at seedling and jointing stages inhibits growth and development, reduces yield in summer maize. *Transactions of the Chinese Society of Agricultural Engineering,* 2013; 29 (5): 44-52.

Appendix A: Mean chemical and physical properties of soil at Vea, before planting at two soil depths (cm) under two slope positions (Danso, 2015)

Soil Property	Footslope		Upslope	
	0-20	20-40	0-20	20-40
Vea				
pH (1:2.5 H_2O)	6.45	6.55	6.1	6.17
Organic carbon (%)	0.72	0.56	0.46	0.40
Total nitrogen (%)	0.02	0.01	0.02	0.01
Aval. Bray P (mg/kg)	5.48	3.01	4.9	3.11
Avail. Bray K (mg/kg)	32.15	46.64	24.28	37.97
Sand (%)	68.4	58.4	67.4	66.2
Silt (%)	29.5	36.2	30.6	32.4
Clay (%)	2.1	5.4	2.0	1.4
Texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Gravel content (%)	32	38	44	43

Soil Property	Soil depth (cm)			
	20	40	60	> 60
DUL* (cm^3 cm^3)	0.15	0.18	0.18	0.18
LL* (cm^3 cm^3)	0.04	0.08	0.08	0.11
SAT (cm^3 cm^3)	0.43	0.39	0.39	0.31
Root growth factor	1.00	0.54	0.36	0.25
Bulk density (g cm^{-3})	1.28	1.34	1.34	1.57
Organic carbon (%)	0.75	1.04	1.04	0.29
pH (1:2.5 H_2O)	6.30	6.30	6.30	7.40
Total N (%)	0.08	0.10	0.10	0.03
Silt (%)	34.00	30.50	30.50	14.40
Clay (%)	1.40	8.50	8.50	21.10
Stone (%)	10	14	14	18

DUL=Drained Upper Limit, SAT=Volumetric water content at saturation, LL=Lower Limit

* values were corrected for gravel content using DSSATs pedotransfer functions

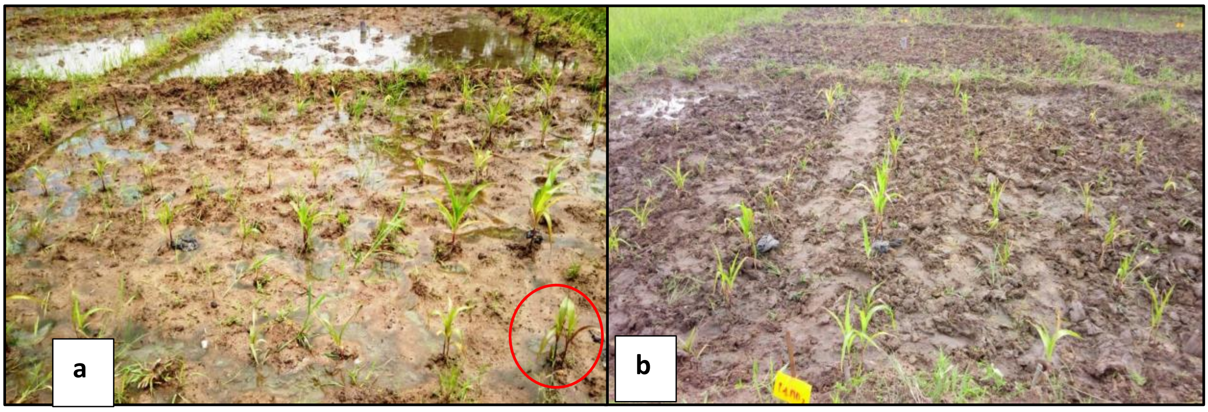
Appendix B: Maize reaction after the flooding flooded days flooding at tasseling and six-leaves stages

A-Maize flooded at tasseling stage with 7-8 cm above the soil surface during 3 days (2018)

B- Maize flooded at V6 stage with 7-8 cm above the soil surface during 6 days (2017)

Appendix C: Constraints during experimentations (fall army wormth attacks during 2017at Boassa (Burkina Faso), waterlogging at Aniabisi (Ghana))

Fall army worm attack during 2017 at Aniabisi



Waterlogging of downslope plot at Downslope during 2017 at Aniabisi

Appendix D: Publications

<u>Peer reviewed papers & book Chapters</u>

- **<u>Daku E. K.</u>** Salack S., Worou O.N., Diallo Y., Diallo O. (2019).Maize response to hypoxia and anoxia at different growth stages under field conditions in Burkina Faso (West African Sahel) submitted to *Agriculture and Water Management Journal* (**Under Review**).
- Salack S., Saley I.A., Lawson N. Z., Zabré I., **Daku E. K.** (2018). *Scales for rating heavy rainfall events in the West African Sahel. Weather and Climate Extremes.* doi:10.1016/j.wace.2018.05.004
- **<u>Daku E. K.</u>** Dossoumou N.I., Worou O.N., Salack S. (2019) Effets de l'engorgement du sol sur la croissance, le développement et la production du maïs In : *Sultan B, Salack S., Bossa A.,et al., Eds: Agriculture et Gestion des RIsques Climatiques : Outils et Recherches en Afrique* (In print).
- Dossoumou N.I., **<u>Daku E. K.,</u>** Worou, O.N, Salack S., Sanfo S., Tondoh J.E., Agbossou E.K. (2019). Effets induits par les risques d'engorgement du sol en maïsiculture au Nord du Ghana. In *: Lupton S, Chauveau-Aussourd V, Randrianasolo-Rakotobe H eds*. Faire face aux risques en agriculture: Perspectives croisées de chercheurs et de professionnels. Paris : L'Harmattan, 57-75

<u>Contributions</u>

- Salack S., Bossa A., Bliefernicht J., Berger S., Yira, Y., Sanoussi K.A., Guug S., Heinzeller D., Avocanh A.S., Hamadou B., Meda S., Diallo B.A., Bado I.B., Saley I.A., **Daku, E.K.**, Lawson, N.Z., Ganaba, A., Sanfo, S., Hien, K., Aduna, A., Steup, G., Diekkrüger B., Waongo M., Rogmann A., Kunkel R., Lamers J.P.A., Sylla M.B., Kunstmann H., Barry B., Sedogo L.G., Jaminon C., Vlek P., Adegoke J., Savadogo M. (2019). Designing Transnational Hydroclimatological Observation Networks and Data Sharing Policies in West Africa. *Data Science Journal,* 18(1), p.33. DOI: <u>http://doi.org/10.5334/dsj-2019-033</u>

Appendix E: Topographical maps of Boassa site (Burkina Faso)