SIMULATING COMMON BEAN PERFORMANCE UNDER SELECTED ENVIRONMENTAL STRESSES FOR IMPROVING INDEX-BASED INSURANCE MODEL AND ITS UPTAKE AMONG FARMERS IN THREE DISTRICTS OF RWANDA

NEPOMUSCENE NTUKAMAZINA

A thesis submitted in fulfilment of the requirements of the award of the Degree of Doctor of Philosophy in Management of Agroecosystems and Environment in the Department of Land Resource Management and Agricultural Technology, Faculty of Agriculture

University of Nairobi

2018

DECLARATION

I hereby declare that this thesis is my original work and has not been submitted for a degree or award in any other university.

Nepomuscene Ntukamazina (A80/99067/2015) Signed…………… Date…3/9/2018

This thesis has been submitted with our approval as university supervisors

Prof. Richard N. Onwonga Signed…………… Date…3/9/2018
Department of Land Resource Management
and Agricultural Technology
University of Nairobi

Prof. John Mburu Signed…………… Date 3/9/2018
Department of Agricultural Economics
University of Nairobi

Dr. Rolf Sommer Signed…………… Date 4/9/2018
International Center for Tropical Agriculture
(CIAT)

DEDICATION

This thesis is dedicated to my wife Jacqueline Ntiringaniza, our children and in memory of my late parents Lazare Ciramunda (1945-1978) and Anatolie Ndabateze (1947-2004).

ACKNOWLEDGEMENTS

My sincere gratitude goes to Prof. Richard N. Onwonga, Dr. Rolf Sommer, Prof. John Mburu, Dr. Clare Mukankusi and Jean Claude Rubyogo for their supervision and guidance during the conceptualisation, implementation and reporting of this research. They tirelessly read and commented on the various manuscripts leading to scientific publications in addition to this thesis. Their strong work ethic, clear guidance, detailed and constructive comments were vital for the successful development of this thesis.

I am deeply indebted to the management of the Department of Land Resource Management and Agricultural Technology and Faculty of Agriculture of the University of Nairobi, the International Center for Tropical Agriculture (CIAT), Rwanda Agriculture Board (RAB), Agriculture and Climate Risk Enterprise (ACRE-Africa), for allowing me to use their research infrastructures and offices without restriction. I also extend my gratitude to my employer, the Institut des Sciences Agronomiques du Burundi (ISABU) for granting me the study leave and permission to further my studies and strengthen my career.

I am thankful to my colleagues working for the bean research programme of Rwanda Agriculture Board, particularly Augustine Musoni, Floride Mukamuhirwa, Alfred Rumongi, Claudine Nibishaka, Justin Tuyiringire, Emmanuel Uzabakiriho, Nazaire Minani, Marcelline Itangishaka, Nzaramba Leonidas, Gasigwa Evariste, Emerance Mukangabo and bean farmers I worked with during the data collection. Without their assistance, this work would not have been possible.

In a special way, I would like to thank Mrs. Capitoline Ruraduma, former leguminous crops research program leader at ISABU (2005-2015), for the assistance in securing and ensuring that the scholarship was awarded to me.

This study was jointly funded by the International Center for Tropical Agriculture (CIAT) and Syngenta Foundation for Sustainable Agriculture (SFSA) through the “Bean Seed System Project”. Their technical and financial support is gratefully acknowledged.

To those who I may have not mentioned by name or institutional affiliation, your unreserved contribution is highly appreciated as it significantly contributed to this thesis.

May God bless you all abundantly.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ACRE	:	Agriculture and Climate Risk Enterprise
ALS	:	Angular Leaf Spot
APH	:	Actual Production History
ARC	:	Africa Risk Capacity program
AYII	:	Area Yield Index Insurance
BCMNV	:	Bean Common Mosaic and Necrosis Virus
BCMV	:	Bean Common Mosaic Virus
CBB	:	Common Bacterial Blight
CCE	:	Crop Cutting Experiment
CIAT	:	International Center for Tropical Agriculture
CRC	:	Crop Revenue Coverage
CRD	:	Completely Randomized Design
DSSAT	:	Decision Support System for Agro-technology Transfer
FAO	:	Food and Agriculture Organization of the United Nations
FMP	:	Future Market Price
GIIF	:	Global Index Insurance Fund
GSMA		Global System for Mobile communication Association
HARITA	:	Horn of Africa Risk Transfer for Adaptation
IBCI	:	Index Based Crop Insurance
IBLI	:	Index Based Livestock Insurance
IFC	:	International Finance Corporation
ISABU	:	Institut des Sciences Agronomiques du Burundi [Agronomic Sciences Institute of Burundi]
IUA	:	Insured Unit Area
MFI	:	Micro-Finance Institute
MPCI	:	Multi-Peril Crop Insurance
NDVI	:	Normalized Deviation Vegetation Index Insurance
NISCO	:	Nyara Insurance Share Company
NPCI	:	Named Peril Crop Insurance
PSNP	:	Productive Safety Net Program
RAB	:	Rwanda Agriculture Board
RRMSE	:	Relative Root Mean Square Error
RSII	:	Remote Sensing Index Insurance
SFSA	:	Syngenta Foundation for Sustainable Agriculture
SSA	:	Sub-Sahara Africa
SUC	:	Standard Unit Contract
WFP	:	World Food Program
WII	:	Weather Index Insurance
WRSI	:	Water Requirement Satisfaction Index

GENERAL ABSTRACT

Index based crop insurance products such as Area Yield Index Insurance (AYII) are widely promoted as a means of addressing climate related constraints for bean crop production. However, in Rwanda, farmers are reluctant to subscribe to the full season cover contract of the AYII product arguing that the product is expensive. This research thus aimed at enhancing AYII to better respond to environmental stresses at different growth and developmental stages of common bean. Greenhouse and field experiment were conducted for two growing periods each during the period from September 2015 to February 2017. In the greenhouse experiment (Sep 2015 – Feb 2016 and Mar 2016 – Jul 2016), the response of bush and climbing bean to excessive and minimal soil moisture at five plant growth stages (emergence, vegetative, flowering, pod setting and seed filling) was investigated. Two bean genotypes (RWR2245 for bush type and MAC44 for climbing type) were used in a Completely Randomized Design with four replicates. For the field experiment (Mar 2016 – Jul 2016 and Sep 2016 – Feb 2017), four bean genotypes (Akararakagenda & RWR2245 for bush type and MAC44 & RWV1129 for climbing type) were used to assess the effect of natural bean disease pressure on bean yield losses in low, medium and high altitude of Rwanda. The field experiment was laid out in a split-split-plot design where the bean genotypes were assigned to the whole plots, plant growth stages with four levels (vegetative, flowering, pod setting and seed filling) to sub-plots and pesticide application with two levels (application and no application) to the sub-sub-plots. Data collected on MAC44 and RWR2245 from both greenhouse and field experiments were modelled with GROPGRO-Dry bean model of DSSAT for simulating bean yield losses due to drought, waterlogging and natural bean disease pressure at the various plant growth stages of common bean. For each treatment, both simulated grain yield and yield reduction rate were fitted in the area yield index insurance model to estimate the subsequent expected premium rate. Seed filling stage was severely affected by waterlogging stress with a yield reduction of 28%. Drought stress significantly affected bean production during seed filling stage with an estimated yield reduction of 23%. Pod setting stage was the most sensitive to natural bean disease pressure with an estimated yield loss of 30%. The corresponding expected premium rates were estimated at 429 kg ha^{-1} for waterlogging stress at seed filling stage, 257 kg ha^{-1} for drought stress at seed filling and 467 kg ha^{-1} for natural bean disease pressure at pod setting. As the AYII product does not covering, in separate contracts, weather stresses that could happen during different plant growth stages, the product was considered inadequate to the needs of resource limited farmers. This study has suggested an anticipated claim formula that insurers can use for diversifying the area yield index insurance product into sub-products from which farmers can select insurance coverage based on their experiences in bean production and their income level (financial means). The formula predicts both actual area yield and corresponding premium rates for drought, waterlogging and natural disease pressure at vegetative, flowering, pod setting and seed filling growth and developmental stages of common bean.

Keywords: bean disease, drought, index-based insurance, *Phaseolus vulgaris,* premium rate, yield loss and waterlogging.

CHAPTER ONE

GENERAL INTROUCTION

1.1. Background information

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume for poor small householder farmers in Sub Saharan Africa (Beebe *et al.*, 2013). It has unusual health benefits being rich in protein (about 22%) and providing a good source of iron and zinc, which are key elements for mental development (Ostyula, 2010; Buruchara *et al.*, 2011). Despite its importance in nutrition and food security, in addition to recent advances in generation of research innovations, dry bean production is limited by unpredictable weather conditions (Katungi *et al.*, 2009). Agricultural insurance is one method by which farmers can stabilize crop production and cope with income losses due to environmental stresses or market prices variability. Crop insurance not only stabilizes the farm income but also helps the farmers to initiate production activity after a bad agricultural year and make more investments in agriculture (Raju and Chand, 2008).

From 2009, Syngenta Foundation for Sustainable Agriculture (SFSA) developed index-based crop insurance products to insure farmers against adverse weather conditions in Kenya, Rwanda and Tanzania. Some of the developed products, particularly Weather Index Insurance (WII) cover only one or sometimes two weather perils omitting other factors that could lead to the crop failure (Tao *et al.,* 2009; Dick *et al.,* 2011). In contrast, the Area Yield Index Insurance (AYII) captures agricultural production risks and provides the most comprehensive cover to farmers.

Agriculture and Climate Risk Enterprise Ltd (CRE-Africa) and MicroInsure have made positive achievements while implementing index-based agricultural insurance in Rwanda.

For example, the number of insured farmers has increased from 20,000 in 2012 to 150,000 farmers in 2014 (ACRE, 2015). However, according to Access to Finance Rwanda -AFR (2015), there is a need to develop affordable insurance packages, as the insurance in Rwanda is still expensive for farmers, especially considering other factors like interest on loans. Giertz *et al*. (2015) suggested reduction of insurance premiums as a key factor to sustain the provision of agricultural insurance in Rwanda and in the region. Particularly, limited resource farmers have been hesitant to buy the full contract cover of area yield index insurance as it is being sold at unaffordable price comparing to their purchase power. Indeed, AYII product is presented to farmers as a full cover insurance product whereas weather index insurance products are sold in insurance sub-products based on the plant developmental stages - example of a three phases maize drought contract (Wairimu *et al*., 2016). In addition, with ACRE-Africa policy, subscribers to AYII (clients) require to wait for payout claiming until harvesting time so that their realized area yield can be compared to the threshold yield (World Bank, 2015). Therefore, there is a need to diversify AYII insurance product into possible insurance sub-products to increase its uptake by limited resource Rwandan bean farmers. In addition, the insurance model should suggest anticipated yield losses to relate comparison between realized yield and insured yield at any time the insured peril is observed during plant growth stages. Crop simulation models readily provide the proper means to analyze the effects of the changes of soil characteristics or weather pattern separately, which would be difficult to achieve under field experiments (Rezzoug *et al.*, 2008; Singh, 2016). The research, with the aid of a crop simulation model (DSSAT), investigated possible environmental stresses to be considered in improving index-based insurance models for common bean. As the Area Yield Index Insurance (AYII) model bears the opportunity to offer the most reliable insurance covers to resource limited farmers, the model was explored for its modification to possible insurance sub-products targeting the susceptible bean plant growth stages to weather perils such as drought, waterlogging and natural bean disease pressure.

1.2. Statement of the problem

In Rwanda, common bean production is constrained by unpredictable rainfall distribution (drought, excessive rainfall), diseases, low soil fertility and limited access to improved seeds (Katungi *et al*., 2010; Buruchara *et al.,* 2011). Area Yield Index Insurance product, being sold as a full season cover contract and widely promoted as a promising strategy to sustain bean production under the changing weather conditions (Raju & Chand, 2008) is not being taken up by the resource limited farmers (World Bank, 2015) Further, the AYII product does not insure weather perils at different plant growth and developmental stages. In addition, the product does not trigger indemnity payment before the end of the cropping season (Dick *et al.,* 2011). To modify AYII for accommodating plant growth and developmental stages to weather related perils would require conducting field experiments over long periods of time to obtain reliable data, a scenario that would be time consuming, expensive and uncertain due to climate change (Chunlei *et al.*, 2013).

1.3. Justification

Area Yield Index Insurance (AYII) product appears to be more relevant for resource limited farmers as it covers yield losses due to various agricultural perils including pests and diseases, for which weather index insurance do not capture. However, relying on its full cover insurance product undermines the value of this insurance product in providing small-holder farmers with protection against weather related perils. Mechanisms of lowering its associated cost are necessary to make the product more affordable to farmers. In contributing to this, the current research explored the area yield index insurance model for its modification to possible insurance sub-products targeting the susceptible plant growth and developmental stages to weather related perils. This will make the product more affordable, attractive to both farmers and insurers and appropriate for its promotion/utilization at national and regional levels. The insurance sub-products tailored to insure different plant growth stages considered most sensitive to the selected weather peril will provide confidence to farmers in producing common bean for income, nutrition and food security. Given that the time and resource constraints associated with field experiments, robust crop simulation models, such as DSSAT, are recommended as they have the capabilities of analysing and estimating separately crop performance as a function of weather, soil conditions and crop management.

1.4. Outline of the thesis and conceptual framework

The thesis is organized into six chapters in addition to the general abstract which provides a brief synthesis of the study with key findings. The general introduction (chapter 1) presents the background information to the problem being investigated, the significance of the study and how it addresses identified research gaps. The literature review (chapter 2) draws up the factors, challenges and opportunities associated with the implementation of agricultural index-based insurance products in SSA. Field experiments were conducted to estimate bean yield losses due to drought, waterlogging and natural bean disease pressure at different plant growth stages of common bean (chapter 3 and chapter 4). Chapter 5 recapitulates the findings resulting from chapter 3 and 4 and that were used to calibrate and validate DSSAT model for estimating bean yield losses and subsequent expected premium rates for an area yield index insurance product.

Chapter 6 provides the overall discussion, conclusions and recommendations. The implementation of this study is summarised into the following conceptual framework (Figure 1).

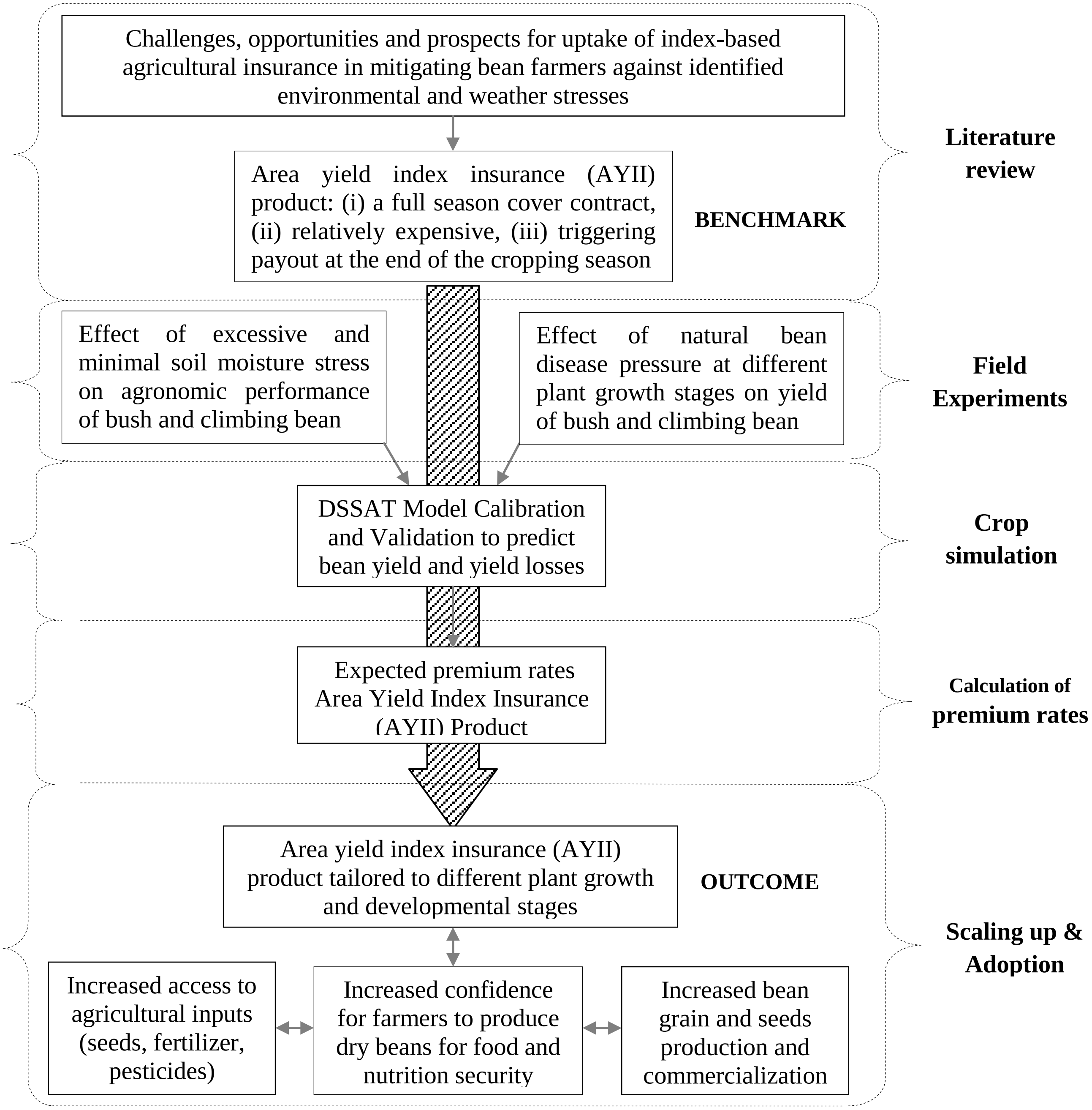


Figure 1: [1.1] Conceptual framework of the study

1.5. Objectives

1.5.1. General objective

To enhance index-based insurance model to better respond to environmental stresses in common bean production systems for income, nutrition and food security.

1.5.2. Specific objectives

1. To determine the effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean types;
2. To assess the effect of natural bean disease pressure on yield loss of common bean in low, medium and high altitude of Rwanda;
3. To calibrate DSSAT model for estimating area yield index insurance premium for common bean at different growth stages and weather perils.

1.6. Hypotheses

1. Reproductive stages of common bean are more sensitive to excessive and minimal soil moisture stresses than vegetative stages;
2. Reproductive stages of common bean are more sensitive to natural bean disease pressure than vegetative stages;
3. The higher the yield loss of common bean due to drought, waterlogging and natural bean disease pressure, the higher the premium rate for an area yield index insurance model.

CHAPTER TWO

LITERATURE REVIEW

2.1. Origin and major classes of common bean

Also known as dry bean, common bean (*Phaseolus vulgaris* L.) is an annual leguminous plant which was introduced to Africa by Portuguese traders in the 16th century where it was met with great success in the Great Lakes region (Mukankusi *et al.,* 2008; Dagnew *et al.,* 2014). Common bean shows variation in growth habits from determinate bush to indeterminate climbing types. The bush bean type is the most predominant type grown in Africa. However, the climbing bean varieties are being promoted and intensively adopted as a response to the problem of small land sizes and high population pressure (Katungi *et al.,* 2009).

Depending on the type of growth habit, the crop requires between 65 and 120 days from planting to maturity. The first half of this period covers the vegetative development while the latter half covers reproductive stages. In climbing types there is an overlap of the two periods because continued vegetative growth occurs after flowering begins. There can be new pods, half developed pods and fully developed pods as well as newly opened flowers present on the same plant. Within common bean species, there are two major classes namely snap bean (French beans) and dry bean. Snap beans are also known as string or green beans and are mainly grown for their pods, while dry beans are mainly grown for their grains (Mukankusi *et al.,* 2008).

2.2. Importance of common bean

2.2.1. Importance of common bean in human nutrition

Among the legumes grown, common bean (*Phaseolus vulgaris*) is ranked as the most popular in both production and utilization, especially for the resource limited farmers (Beebe *et al.*, 2013). In Latin American countries, the national bean consumption per capita is between 12 and 18 kg per year (Broughton *et al.*, 2003). In rural Nicaragua, bean consumption per capita can be as high as 36 kg per year among the more affluent communities (FAO, 2011). In Africa, bean consumption can be as high as 60 kg per capita per year in countries like Rwanda, Burundi or in western Kenya (Beebe *et al.*, 2013).

Dry bean provides a good source of protein at minimal cost compared to animal protein sources and also enrich the diet with several vitamins, mineral nutrients such as iron, zinc, calcium, copper, magnesium, manganese, and phosphorus (Broughton *et al.*, 2003). The contribution of iron to the diet is particularly vital in developing countries where nutritional anaemia due to iron deficiency is widespread (Worall *et al.*, 2015). An increased intake of dry beans will provide nutritional benefits to the diet, and may help to reduce malnutrition status, particularly for resource limited small holder farmers (Chilagane *et al.*, 2013). Table 1 provides an example of the nutritional profile of cooked dry beans. Common bean protein is high in lysine, which is relatively deficient in maize, cassava and rice, making it a good complement to these staples in the diet (Katungi *et al.*, 2009). Thus dry beans play an essential role in the sustainable livelihoods of smallholder farmers, providing both nutrition and food security. Any advances in scientific research that benefit bean yields, particularly in developing countries, help to feed the hungry and give hope for the future (Jones *et al.*, 2003).

Table 1: [2.1] Nutritional profile of cooked black bean grains (~40 g)

Elements	Content	Element	Content	Element	Content
Calories (Cal)	113	Fat & Saturated fat (g)	< 1	Thiamin (mg)	< 1
Carbohydrate (g)	20	Potassium (mg)	306	Sodium (mg)	1
Protein (g)	8	Folic Acid (mcg)	128	Copper (mg)	< 1
Dietary fibre (g)	8	Phosphorus (mg)	120	Manganese (mg)	< 1
Iron (g)	2	Magnesium (mg)	60	Cholesterol (mg)	0

Source: Raatz, 2017

2.2.2. Importance of common bean in income generation

Common bean is increasingly becoming a significant source of income for smallholder farmers (Worthman *et al.*, 1998). Dry bean seeds can be classified into nine major commercial market classes. These include the Calima (Rosecoco or red mottled), large and small reds, navy, cream-coloured, brown tan, yellow, purples, white and black beans. Calima and reds account for about 50% of production in Africa due to their high market demand (Mukankusi *et al.*, 2008). In Mexico for example almost 100,000 tons per year are transformed into canned beans which generate significant income to traders as 1 kg of dry bean yields up to 3.5 kg of canned bean product (Beebe *et al.*, 2013).

In Rwanda, planting improved bean varieties has increased household bean revenues by 11,971 Rwanda Francs (49.99 USD) per season (Larochelle *et al.*, 2015). Whereas in Burundi, the high bean production always leads farmers to put a part of their produce on a commercial orientation, particularly in the higher bean growing provinces of the country such as Kirundo, Muyinga, Ngozi, Karusi and Gitega (Birachi *et al.*, 2011; Ochieng *et al.*, 2014).

2.3. Bean production constraints

2.3.1. Water-related bean production constraints

Common bean grows well and has high yield and quality potential when the soil water in the active root zone is kept between 60 and 100% of the available water-holding capacity of the soil. As suggested by Efetha (2011), applying irrigation just before the soil water is depleted to 60% of available and replenishing available soil water near field capacity in appropriate root zones will greatly assist in producing a high quality and high yielding dry bean crop (Table 2). The optimum rainfall for maximum production of a 60 to 120-day bean crop cultivated under rain fed conditions varies between 300 and 500 mm (Nieto *et al.*, 2006). On average, dry bean water use ranges from 0.1 mm per day soon after emergence to nearly 7 mm per day during flowering and early pod development stages (Efetha, 2011).

Table 2: [2.2] Soil texture-based estimation of amount of water per irrigation event for dry bean

Soil texture	Vegetative (pre-flowering) stages		Flowering to grain filling stages	
	Available water in a 30-cm root zone (mm)	Water required to replenish soil to FC at 40% allowable depletion (mm)	Available water in a 60-cm root zone (mm)	Water required to replenish soil to FC at 40% allowable depletion (mm)
Loamy sand	34	14	68	28
Sandy loam	42	17	84	34
Loam	54	22	108	43
Sandy clay loam	46	18	91	36
Silt loam	60	24	120	48
Clay loam	60	24	120	48
Silt clay loam	66	26	132	53
Sandy clay	52	21	103	41
Silt clay	64	26	127	51
Clay	58	23	115	46
FC=Field Capacity				

Source: Efetha, 2011

Drought

In recent years, inadequate total rainfall, erratic rainfall distribution, long dry spells and delayed onset or early cessation of rains had contributed to decreased bean production (Katungi *et al.*, 2009). According to Rosales *et al.* (2012), drought stress is one of the limiting factors with significant reduction of crop growth and yield (Emam and Seghatoleslami, 2005). In the developing world, more than 60% of common bean production is conducted in drought prone areas (Graham & Ranalli, 1997). This is probably the reason why the average global common bean yield remains as low as 900 kg ha^{-1} (Singh, 2001; Nieto *et al.*, 2006). Particularly, drought stress during flowering and grain filling, cause significant yield reductions (Emam *et al.,* 2010). Therefore, bean growers are encouraged to properly manage irrigation by regularly monitoring soil water to ensure that the availability of water does not become a limiting factor for bean production (Rosales *et al.*, 2012).

Excessive water

Flooding or waterlogging has been recognized as a serious problem for crop production particularly in many river valleys and delta areas where farmlands are constantly affected. Worldwide, more than 30% of the agricultural land is affected by waterlogging (Uddin *et al.*, 2013). Excessive water stress is primarily caused by either irrigation without drainage, over-irrigation, or low delivery efficiency of the irrigation due to malfunctioning of drainage system (Backlund *et al.,* 2008). As indicated by Ahmed *et al.* (2013), one of the main physiological effects of waterlogging is an inhibition of photosynthesis. Excessive water reduces oxygen concentration around plant roots, restricts nodule activity and nitrogen fixation. Consequently, this leads to reduction of nutrient availability, microbial activity, plant respiration, energy production and the accumulation of phytotoxic products such as ethylene (Backlund *et al.,* 2008).

The latter (ethylene) is known as a root growth inhibitor with varying effects on different crops (Kumar *et al.,* 2017). These factors combine to hamper plant growth with ultimate consequence of reducing yield. Kumar *et al.* (2017) reported photosynthetic loss of 43, 51 and 63%, and grain yield loss of 20, 34 and 52%, for mung bean at 3, 6 and 9 days of waterlogging, respectively.

2.3.2. Bean diseases

Common bean production is also impacted by disease attack during its growing cycle. The source of plant contamination can be intrinsic (seed-borne diseases) or extrinsic to bean seed. Seed-borne diseases arise from internal contamination or being carried in the seed (Musoni *et al.*, 2010). Whereas extrinsic source of bean disease is due to insects that attach or contaminate plant in the field or through the damage they cause to seed in the storage or in the field prior germination (Buruchara *et al.,* 2010).

In most of bean growing areas of Africa, the most reported bean disease include (but not limited to) root rot (*F. Phaseoli, R. solani, C. rolfsii, Pithium sp)* Angular leaf spot (*P. griseola),* Anthracnose (*C. lindemuthianum),* Rust (*Uromyces appendiculatus),* Ascoschyta leaf spot *(Phoma exigua var. exigua, Ascochyta phaseolorum)* Common bacterial blight (*Xanthomonas campestris*), Bean common mosaic virus (BCMV) and Aphids (*Aphis fabae).* Particularly, early infection of susceptible cultivars by root rot, angular leaf spot and bean common mosaic viruses can cause yield loss up to 100% (Mwango'ombe *et al.*, 2007; Wahome *et al.*, 2011; Li *et al.,* 2015; Worall *et al.,* 2015).

Several disease control strategies have commonly been advocated in attempt to reduce losses caused by pests and bean diseases. These include use of tolerant varieties, planting disease-free seeds, field sanitation, soil amendment with compost, crop rotation, intercropping and pesticides

(Mwango'ombe *et al.,* 2007; Musoni *et al.,* 2010; Wahome *et al.,* 2011). However, effectiveness of these methods is limited by the high pathogenic variability (Wagara *et al.,* 2005), land unavailability to practice crop rotation, ability of the pathogen to survive in plant debris for long period of time (Chilagane *et al.,* 2013) and unavailability and high cost of certified seed (Buruchara *et al.,* 2011).

Smallholder bean farmers mainly rely on pesticides (fungicides and insecticides) to prevent or reduce post-harvest losses associated with pests and diseases (Wasonga *et al.,* 2010). However, continued use of chemicals also leads to emergence of disease resistant pathogen races, increased production costs and negative effect on the environment and human health (Kimani, 2001). Based on these limitations, the use of disease tolerant cultivars can be most feasible, sustainable and cost effective disease control measure especially among the land-scarce and resource poor farmers (Musoni *et al.,* 2010).

2.3.3. Soil fertility and agronomic practices

Due to the high population density, farmers are facing rapid soil fertility decline as a result of continuous cropping and inappropriate cropping systems. According to Lunze *et al.* (2012), about 22% of bean production area in Africa is sole cropped, 43% in association with maize, 15% with bananas, 13% with root and tuber crops, and 7% with other crops. With very little or no external nutrient inputs to replenish the soil fertility, high cost of fertilizers inputs, bean yield is generally low in most regions and is most likely to decline. Already, Kimani *et al.* (2001) reported bean grain yields from 200 kg ha^{-1} in less favourable environments to 700 kg ha^{-1} in more favourable environments when grown in pure stands, and about half when intercropped. However, promising integrated soil fertility management (ISFM) options exist. These options include use of bean genotypes for low soil fertility, farmyard manure, compost, biomass transfer, green manure and cover crops, liming, phosphate rock (PR) and mineral fertilizers (Otieno *et al.*, 2007). Application rates for nitrogen (N), phosphorus (P) and potassium (K) are estimated based on the soil fertility level before planting (Table 3).

Table 3: [2.3] Suggested rates of Nitrogen, Phosphorus and Potassium for dry bean fertilization

Element	Soil fertility status prior planting		Fertilizer application rate	
	ppm in soil	Relative level	kg acre^{-1}	kg ha^{-1}
Nitrogen (N)	0-15	low	24	60
	15-30	medium	12	30
	>30	high	0	0
Phosphorus (P)	0-6	low	16	40
	7-14	medium	8	20
	>14	high	0	0
Potassium (K)	0-60	low	16	40
	61-120	medium	8	20
	>120	high	0	0

Adapted from Davis & Brick, 2009

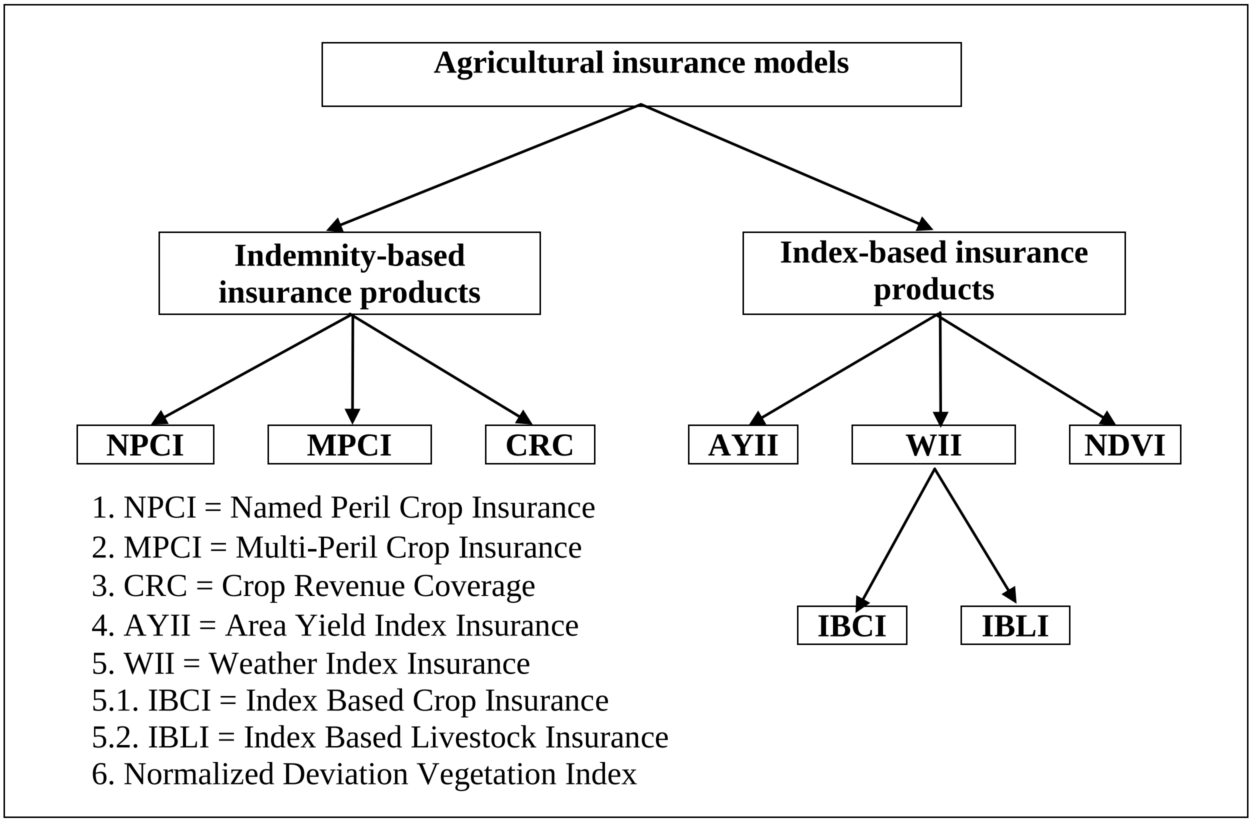
2.4. Crop insurance models

2.4.1. Rationale of crop insurance

In most cases, crop loss coping strategies for rural households do not provide sustainable solution to cope with weather related crop production risks (Liu *et al.*, 2007). Through appropriate on-farm risk mitigation techniques (irrigation, pest prevention, self-insurance tools, savings and contingent credit) farmers can retain only small losses. However, the relatively severe and frequent systemic losses due to drought, flood, windstorm, and freeze, need to be transferred to commercial insurers and reinsurers (Moorhead *et al.*, 2009). Therefore, crop insurance is a major component of risk management that farmers could use together with climate information to optimize their risk-return characteristics (Liu *et al.*, 2007).

2.4.2. Types of agricultural insurance products

According to World Bank (2009), there are seven crop insurance products classified into two categories: Indemnity-based crop insurance and index-based insurance products (Figure 2).



1. NPCI = Named Peril Crop Insurance
2. MPCI = Multi-Peril Crop Insurance
3. CRC = Crop Revenue Coverage
4. AYII = Area Yield Index Insurance
5. WII = Weather Index Insurance
5.1. IBCI = Index Based Crop Insurance
5.2. IBLI = Index Based Livestock Insurance
6. Normalized Deviation Vegetation Index

Figure 2: [2.1] Agricultural insurance models (Adapted from Ntukamazina *et al.* 2017)

Named Peril Crop Insurance

Also called damage-based indemnity insurance, named peril crop insurance (NPCI) is an insurance product where the claim is calculated by measuring the percentage crop damage in the field, soon after the occurrence of the insured peril (World Bank, 2010). Where damage cannot be measured accurately immediately after the loss, the assessment may be deferred until later in the crop season. This insurance is best known for the hail but it is also used for other named perils such as frost, excessive rainfall, and wind (Barrett *et al.*, 2007).

Multiple Peril Crop Insurance

Multiple perils (yield based) crop insurance products provide insurance against all perils that affect production unless specific perils have been explicitly excluded in the contract of insurance (Hazell *et al.,* 2010). The MPCI assures a percentage of the farmers' historic yield. If the yield becomes lower than the insured percentage, the insurance pays an indemnity covering the difference between the insured percentage and the realized yield. The insured yield (such as tons per hectare) is established as a percentage of the historical average yield of the insured farmer. The insured yield is typically between 50 and 70 percent of the average yield on the farm, or set in the range of 50 percent to 70 percent of the expected yield (World Bank, 2009). The calculation of the payout is based on the extent to which the actual yield falls short of the guaranteed yield at the agreed price or as the shortfall in yield as a percentage of the guaranteed yield applied to the sum insured (Nieto *et al.*, 2006). If the actual/realized yield (AY) is less than the insured/guaranteed yield (GY), an indemnity is paid equal to the difference between the actual yield and the insured yield, multiplied by an agreed value of future market price (FMP) and insured unit area (IUA).

Crop Revenue Coverage

Insurance against poor crop yields has been available for many years. However, income from crop production can be low even when yields are not. A risk management tool known as Revenue Protection (RP) insurance addresses this problem. Revenue Protection insurance guarantees a certain level of revenue rather than just production. It protects insured from declines in both crop prices and yields. The guarantee is based on market prices and the actual yield on farm (Edouard & Plastina, 2014).

Yield coverage for this product is the same as for traditional yield protection insurance, i.e. the Actual Production History (APH), which is an historic average of actual yields (Hazell *et al.*, 2010). The Revenue Protection uses future market prices and APH yields to compute revenue coverage and guarantee. Using the monthly average crop future prices both harvest and projected price are determined. The final revenue guarantee is computed by multiplying the higher of either the projected price or the harvest market price by the APH yield for the farmer, by the chosen coverage level between 50 to 85% (Dick *et al.*, 2011). A farmer receives an indemnity payment if the actual revenue falls below the revenue guarantee. The main challenge facing the implementation of crop revenue insurance is the lack of local commodity future market prices (World Bank, 2010).

Area-Yield Index Insurance

The key feature of this product is that it does not indemnify crop yield losses at the individual field or grower level. Rather, an area-yield index insurance product makes indemnity payments to growers according to yield loss or shortfall against an average area-yield (the index) in a defined geographical area. Indemnity is based on the realized average yield for a defined area such as a county or a district (Daron & Stainforth, 2014). Consequently, farmers who buy the same contracts for AYII in a given region pay the same premium rate for a standard unit contract (SUC) and receive the same pay-out per SUC if the insured peril occurs (Barnett & Mahul, 2007). The insured yield is expressed as a percentage (coverage level between 60-95%) of the historical average yield for a defined crop in the defined geographical region, considered as insured unit (World Bank, 2009). Whenever the realized area yield falls below this trigger yield level (i.e strike), each producer, regardless of his own yield, receives an indemnity equal to the shortfall in the area yield times his elected level of coverage (Miranda, 1991).

In addition to the reduced administrative costs, AYII offers the following advantages (i) information regarding the distribution of the area yield is generally available and more reliable than information regarding the distributions of individual yields, (ii) as the indemnities are based on the area yield rather than the producer's yield, a producer could not significantly increase his indemnity by unilaterally altering his production practices (moral hazard would be eliminated), (iii) AYII covers multiple perils yield losses caused by weather risks such as drought, flooding, pest and disease (Miranda, 1991), (iv) while traditional MPCI is often constrained by a lack of reliable historical yield data at the individual farm level, the required 10 years' historical data at country, district or county level are usually available to determine the coverage level for area yield index insurance contracts (Mahul *et al.*, 2009; Rao, 2010).

Weather Index Insurance

Weather index insurance (WII) is insurance where the indemnity is based on realizations of a specific weather parameter measured over a specified period of time at a particular weather station (World Bank, 2009). The insurance can be structured to protect against index realizations that are either so high or so low that they are expected to cause crop losses (Dick *et al.*, 2011). For example, the insurance can be structured to protect against either too much or too little rainfall. An indemnity is paid whenever the realized value of the index exceeds a specified threshold (protection against too much rainfall) or when the index is less than the threshold (when protecting against too little rainfall). The indemnity is calculated based on an agreed sum insured per unit of the index (World Bank, 2009).

The most important constraint associated with weather index insurance is the basis risk. This risk represents the difference between the loss experienced by the farmer and the payout triggered.

It could result in a farmer experiencing yield loss, but not receiving a payout, or in a payout being triggered without any loss being experienced (Hazell *et al.,* 2010). Weather index insurance normally covers only one, or sometimes two, weather perils and depends on the availability and quality of weather data, which can drastically vary from country to country. In developing countries, the shortage of historical and real-time weather data is often a major challenge (Mahul *et al.,* 2009).

As of February 2018, most weather index insurance (WII) efforts have focused on the risk of rainfall deficit (drought) and such an index insurance model is less useful where more complex conditions exist. In addition, weather index insurance is not suitable for localized risks, such as hail, or where differences in microclimate exist (World Bank, 2010). Similarly, the scope for weather index insurance is limited where crop production is impacted by many or complex causes of loss (as may be the case in the humid subtropics), or where pests and disease are major influences on yields. For a given environment, other insurance products, such as area-yield index insurance or named-peril crop insurance, may be more appropriate (Dick *et al.,* 2011).

Index based crop insurance: The index-based crop insurance (IBCI) product is an innovative form of index insurance that covers farmers against weather-related extreme events. The product uses a proxy (or index) such as the amount of rainfall, temperature, wind speed, relative evapo-transpiration, etc… For example, the rainfall index derivative for wheat in Morocco, the *Kilimo Salama* insurance in Kenya, Tanzania and Rwanda, and the Nyala Insurance Share Company (NISCO) in Ethiopia, indemnity payments are made, for the selected crop, when actual rainfall in the cropping season, recorded in the nearest weather station, falls below pre-defined threshold levels (Dercon *et al.,* 2014; Wairimu *et al.,* 2016). In Malawi, the COINRe re-insurance organisation in collaboration with local insurance companies piloted the use of relative evapotranspiration (RE) as an index instead of using the rainfall index (Leblois *et al*., 2014).

The defined index helps to determine whether farmers have suffered losses from the insured peril and hence need to be compensated. Therefore, the index is set so as to correlate, as accurately as possible, with the crop losses suffered by the policyholder (World Bank, 2011; Tadesse *et al.*, 2015, Wairimu *et al.*, 2016). For example, a maize drought contract offered by Agriculture and Climate Risks Enterprise (ACRE-Africa) in Kenya consists of three phase contract, where for each phase different minimum rainfall requirements apply.

When the rainfall measures below the defined minimum threshold in a block of 5 to 10 days, a pay-out is triggered. The length of each phase, its relative importance, and the minimum thresholds are determined using the FAO's water requirement satisfaction index (WRSI) with the local historical climate data, crop variety characteristics and farmer feedback. An example is shown in Figure 3 for ACRE-Africa index-based insurance cover options including a medium to long maturing maize variety in central Kenya.

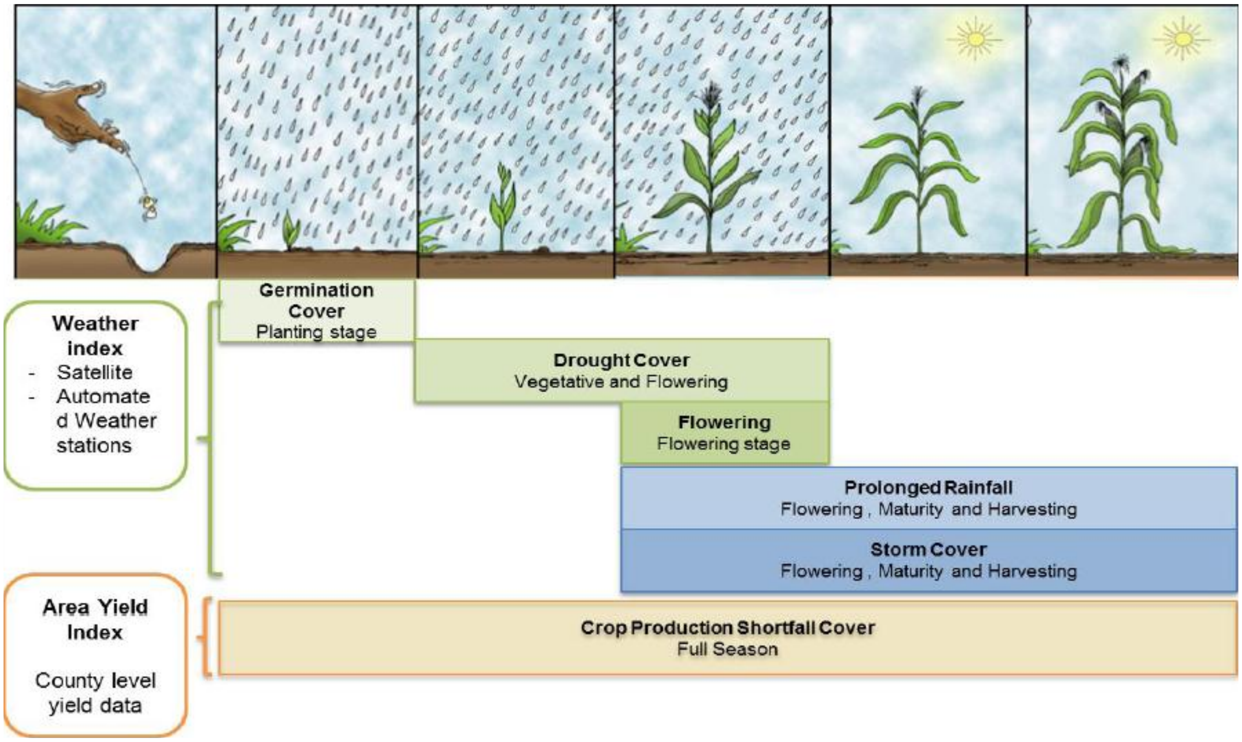


Figure 3: [2.2] ACRE-Africa index-based insurance cover options (ACRE-Africa, 2015)

Index based livestock insurance: The lack of a comprehensive 100-year mortality database has led the International Livestock Research Institute (ILRI) to explore the use of satellite images in designing index based livestock insurance. Mude *et al.* (2010) found the NDVI is highly correlated with forage availability and therefore can be linked to animal mortality. In addition, NDVI data are publicly available in near-real time and objectively verifiable, also widely used, as indicator of vegetative cover in drought monitoring programs in Africa (Chantarat *et al.*, 2009; Jensen *et al.*, 2015). A predicted livestock mortality index is established from a statistical relationship between satellite-generated vegetation imagery and historical records of community level livestock losses. This process generates a parameter that is objectively, cost effectively measured and non-human modifiable as an index that triggers insurance pay-out index (McPeak *et al.*, 2010; Greatrex *et al.*, 2015).

In Kenya and Ethiopia, remotely sensed NDVI measures were used to set up an IBLI based on the relationship between predicted forage availability and livestock mortality (Chantarat *et al.*, 2011; Greatrex *et al.*, 2015). The insurance product covers the short rains short dry season (SRSD) or the long rains long dry season (LRLD). The contract is specific at the location level, based on the predicted mortality rate as a function of the vegetation index specific to the grazing range of that location (Chantarat, 2009). The IBLI contracts are sold just before the start of rainy season and are assessed at the end dry period to determine whether indemnity payments are to be made (Figure 4).

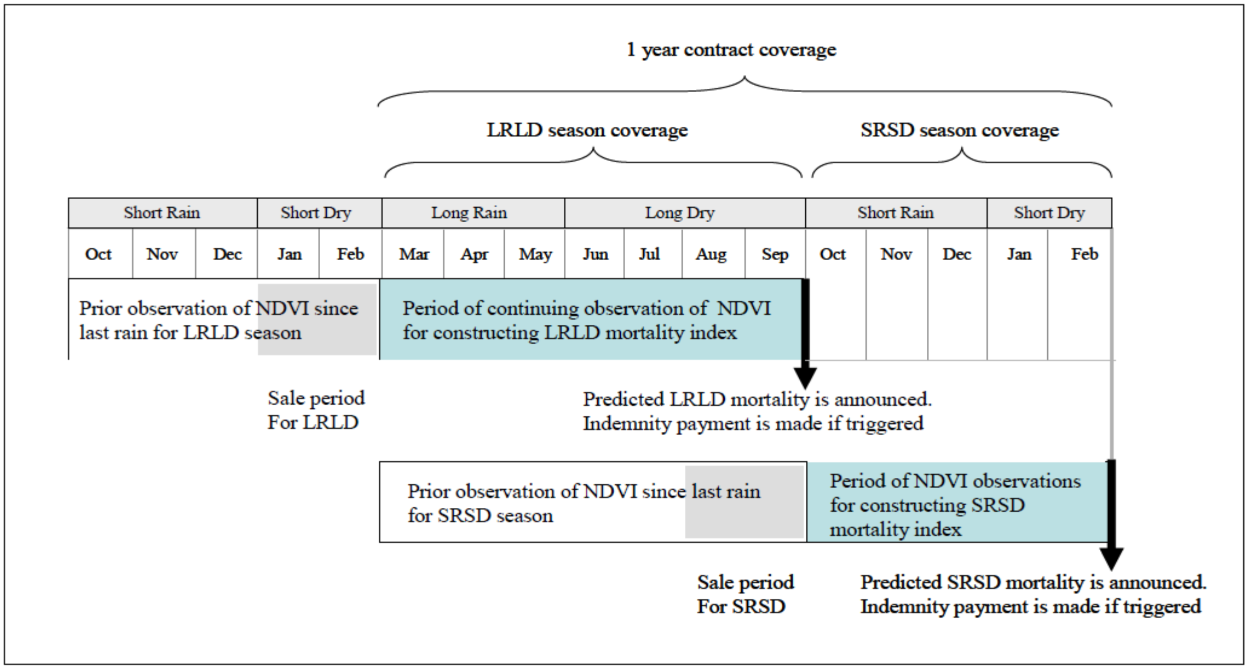


Figure 4: [2.3] Temporal structure of index based livestock insurance contract (Chantarat, 2009)

Normalized Difference Vegetation Index Insurance

The normalized difference vegetation index (NDVI) quantifies vegetation measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). NDVI is a standardized way of measuring healthy vegetation with values always ranging from -1 to +1. Negative, zero and positive values of NDVI indicating water, no green leaves and dense green leaves, respectively (Blanco *et al.,* 2008). The National Aeronautics and Space Administration (NASA) found NDVI as a good indicator of drought, when water limits vegetation growth; it has a lower NDVI and density of vegetation. For example, in pasture index insurance, NDVI uses time-series remote-sensing imagery to get biomass index that relates moisture deficit to pasture degradation (World Bank, 2010). West African grain farmers found the most promising contract to be one based on the NDVI, a remotely sensed, satellite-based measure of the greenness of the vegetation, and as such a proxy for its biomass and/or density (Hill, 2010).

Although NDVI can be more effectively used for monitoring pastoral forage and livestock losses, its use for crops like coffee and bananas would be limited, because losses often do not correlate with extent of vegetation change, reduction and damage (FSD Kenya, 2013). In addition, accuracy of NDVI is limited below 100 km^2 area due to the quality of imaging; Areas of that size still contain a wide range of diverse weather.

2.4.3. Factors influencing uptake of index-based insurance products

While assessing and documenting factors influencing farmers to purchase insurance products in SSA, Ntukamazina *et al.* (2017) found that socio-demographic and socio-economic factors are considered as driving factors for farmers to adopt index-based insurance products, in addition to premium rates and delivery channels (Table 4). As expected, the higher the premium rate, the lower the farmers’ willingness to purchase index-based insurance. Literacy and on-farm income/savings have a positive impact on farmers’ willingness to adopt insurance. While age of farmer and increase in farm size decreases the willingness to adopt insurance products.

However, land ownership and family size were found to have either positive or negative effect on the willingness of farmers to adopt crop insurance products.

Table 4: [2.4] Summary results on factors explaining adoption of index insurance products

Independent variables	Relationship with dependant variable[!] (estimated coefficient)				
	A	B	C	D	E
Premium rates/bid	negative	negative	negative (-0.125)	negative (-0.24)	Negative
Socio-demographic factors					
Years of education	positive (0.063)	positive (0.807)	positive (0.012)	positive (0.09)	positive (0.490)
Age of farmer	negative (-0.172)	*	negative (-0.009)	negative (-0.003)	negative (-0.048)
Family size	negative (-0.126)	positive (0.222)	negative (-0.023)	positive (0.0001)	*
Socio-economic factors					
On-farm income and savings	positive (0.803)	positive (0.242)	positive (0.008)	positive (0.001)	positive (0.0001)
Land ownership	negative (-0.194)	negative	*	positive (0.002)	negative (-2.207)
Farm/herd size	negative (-0.433)	negative (-0.091)	negative (-0.012)	*	negative (-0.131)

A: Wairimu *et al.*, 2016; **B**: Koloma, 2015; **C** : Takahashi *et al.*, 2016; **D** : Gallenstein *et al.*, 2015, **E**: Aidoo *et al.*, 2014

*Independent variable not included in the model

[!] Willingness of farmers to adopt index-based insurance product

Source: Ntukamazina *et al.*, 2017

Higher **premium rates** (or lower expected returns) result in substantially lower levels of participation in agricultural insurance programs. According to Smith & Watts (2010), prior 1980, when insurers were paying premium rate of 80% to the American agriculture insurance company, participation rates were less than 20%; when the premium rate was decreased at 50% (1990-2001) the participation rates grew about 70%. Also, Arshad *et al.* (2015) reported that a unit increase in premium rate decreases the levels of participation in agricultural insurance programs by 0.03.

Literacy has a positive relationship with the willingness of farmers to adopt agricultural insurance scheme (Aidoo *et al.*, 2014; Arshad *et al.*, 2015; Koloma, 2015; Lin *et al.*, 2015). Index based insurance products can be difficult to understand especially for populations with low literacy rates and little or no previous insurance experience. Therefore, education may facilitate the diffusion of new technology and as such has a positive relation with innovation adoption and the payment of accompanying charges. While studying the willingness to pay for crop insurance, Smith & Watts (2010) also reported that farmers with more literacy rates were more interested in rainfall insurance and willing to pay higher amounts. More educated farmers are likely to appreciate crop insurance issues better than their less educated counterparts.

Family size also positively affected the willingness to pay, exposing a potential market for insurance among households having a large number of family members. An increase in family size increases the probability of having access to micro-insurance. The higher the family workforce is, the higher the probability of becoming a micro-insurance beneficiary (Koloma, 2015). Archad *et al.* (2015) indicated also that the joint family system in rural areas can positively influence the decision on making investments like purchasing insurance contracts. In contrast, Wairimu *et al.* (2016) and Takahashi *et al.* (2016) reported that a unit increase in family size decreases the adoption of insurance product by 0.126 and 0.023, respectively.

Aidoo *et al.* (2014) pointed out a negative influence of **age of farmer** on willingness to adopt crop insurance. As farmers grow older they gain more experience in farming through learning by doing, and are more likely to accept risks than younger farmers. In addition, older farmers are less likely to be receptive towards newly introduced technologies. Dercon *et al*. (2014) found in Ethiopia that households with younger household heads who hold official positions are more likely to purchase crop insurance.

On-farm savings were found to have a positive effect on payment of insurance premium. Both Giné & Yang (2009) and Cole *et al.* (2012) found, that insurance uptake is correlated with farmers' wealth. Indeed, insurance premium is usually paid from current income or accumulated income (represented by savings). According to Giné & Yang (2009), the lack of access to credit has traditionally been considered a major obstacle to technology adoption and development. In addition, since the agricultural insurance policies are purchased at the onset of the season, coinciding with the purchase of other agricultural inputs (labour for land preparation, seeds, fertiliser, etc.) only the better-off can afford the policy (Gené & Yang, 2009).

On-farm income is positively correlated with the amount farmers are willing to pay as insurance premium. Indeed, premiums are paid with income and hence farmers with high farm income tend to have higher payment capacity than those with low farm income, *ceteris paribus*. Skees & Barnet (2006) reported that many of the poorest farmers in Tanzania indicated that they simply could not afford to pay any insurance premiums (at least prior to harvest) because their cash flow situation was so dire and their incomes and wealth were so low. Similarly, Smith & Watts (2010) reported that Moroccan farmers with relatively high incomes were more likely to consider purchasing rainfall insurance than farmers with low incomes (quite possibly also because of cash flow problems).

Aidoo *et al.* (2014) found that farmers who **own lands** are less willing to adopt crop insurance compared to tenants and sharecroppers. Such farmers have the capacity to diversify into other enterprises since they have easy access to land. In addition, farmers who own lands do not have to pay anything to anybody in case of crop failure but rather manage the little at their disposal.

It is therefore not surprising that tenants and sharecroppers tend to be more willing to adopt new innovations such as crop insurance to cope with production risk.

In contrary, Barrett *et al.* (2007) reported that farmers who owned land were willing to adopt crop insurance since they have full control over the land and therefore have enough resources to enable them adopt new innovations. Similarly, for land conservation technologies that enhance land fertility and the overall value of the land, land tenure has a positive relationship with willingness to adopt such innovations (Kong *et al*., 2011). This finding is consistent with the work done by Arellanes and Lee (2003) who reported that farmers with security of their own land were four times likely to employ more of new technology due to security of land access and usage.

Farm size was found to have a negative correlation with the adoption of crop insurance. Such farmers have the capacity to diversify into other crops and enterprises since they have easy access to land (Aidoo *et al.*, 2014). However, in other adoption studies a positive correlation was found between willingness of farmers to adopt an innovation and farm size. This was because larger farm sizes tend to have more advantage from adoption of innovations due to economies of scale (Osipenko, 2015).

Delivery channels

As insurers normally have limited or no business (or offices) in rural areas, distribution is best organized through existing links to farmers or farmer groups (Dick *et al.*, 2011). The insurance product distribution through existing services or networks operating in rural areas is important to increase coverage, reduce transaction costs, and reach more clients. Complementary support for agricultural insurance operations could include the promotion of “aggregators”; that is, farmers associations, cooperatives, producer associations, rural banks, and microfinance institutions as delivery channels for agricultural insurance (World Bank, 2010).

For instance in Kenya, Kilimo Salama Insurance is distributed using local stockists at the time of purchasing inputs, making it easier for the customer to adopt the new product. This distribution channel capitalizes on existing relationships since farmers are more likely to take advice from someone they know and trust (World Bank, 2015). Dercon *et al*. (2014) and Tadesse *et al.* (2015) found the uptake of weather index insurance higher in Ethiopia when insurance is channelled through group-based informal insurance schemes *iddir* (a funeral society in Ethiopia) with appropriate training for group leaders.

2.4.4. Challenges for index-based insurance products

Despite the apparent advantages of the index based insurance products, pilot and feasibility studies have shown challenges inherent with index products (World Bank, 2010; FSD-Kenya, 2013). As presented by the International Finance Corporation (IFC), weakness of insurance regulatory environment and poor financial facilities are considered as country/programme specific challenges that impede development of insurance markets in SSA. In addition, uptake of insurance products is impeded by the cross cutting challenges such as basis risk, quality and availability of historical weather and yield data, capacity building of stakeholders (farmer, insurer and regulator), limited product options for different weather risks, and lack of innovation for local adaptation and scalability.

Regulatory environment and financial facilities

Poor regulatory environment and collaboration with financial institutions are reported as country/programme specific challenges to implementing agricultural insurance in SSA (World Bank, 2015). These challenges include weakness of insurance regulatory environment, reluctance of banks and micro-finance institutes to finance agriculture sector, disbursement of loans too late for the planting season leading to a late sowing phase for farmers and higher risk exposure, and absence of financial institutions in rural areas (Mude *et al.,* 2010). Mensah *et al.* (2017) found lack of agricultural insurance legislation and low collaboration with financial institutions among the most pressing constraints that faced the development of agricultural insurance for cashew crop farmers in Ghana. While promoting private sector approaches to help farmers to access index insurance in Kenya, Global Index Insurance Facility (GIIF), Syngenta Foundation for Sustainable Agriculture (SFSA) and International Livestock Research Institute (ILRI) found that there was a need to address restrictive regulations in insurance provision (World Bank, 2015). Fortunately, Insurance Regulatory Authority (IRA) has been established in Kenya and Uganda in addition to the regional body of the insurance industry for 14 countries in Francophone Africa. In addition, GIIF has defined a strategy of providing legal and regulatory assistance to these bodies for public policy dialogue and regulatory environment facilitation to address insurance market failures (Mahul *et al.,* 2012).

Basis risk

Basis risk is the most problematic feature of index-based insurance products, which means that pay-outs may not be fully correlated with crop losses. It represents the difference between the pay-out, as measured by the index, and the actual loss incurred by the policyholder. The higher the positive correlation between the farm and county yield, the lower the basis risk and vice versa (Barnett *et al.*, 2005). Because no field loss assessment is made under index insurance, the pay-out is based entirely on the index measurement and may be either higher or lower than the actual loss (World Bank, 2010). Microclimates and uneven topography may affect the yields greatly and these aspects are sometimes not accurately factored into the product design (Bageant & Barnett, 2015). There has been significant research aimed at addressing basis risk by increasing the density of automatic weather stations (every 10-15 km) or designing hybrid index insurance products using a combination of satellite-rainfall estimates and vegetation indices (Greatrex *et al.*, 2015). Lowering the size of insured unit and double or triple trigger mechanism were also presented by World Bank (2009) and Stoeffler *et al.* (2016) as ways to minimize the basis risk. For example, the Burkinabé index insurance, pay-out occurred only if both the cooperative yield is below the cooperative strike-point (e.g. 750 kg ha^{-1}) and the district yield is below the district strike-point (e.g. 1,000 kg ha^{-1}). In Mali, the cotton area-yield insurance provided three level payments: small pay-out, medium pay-out and big pay-out when yields were below 20%, 8% and 4% of the yield distribution (Stoeffler *et al.*, 2016).

Quality and availability of weather and yield data

The development of index based insurance products requires accurate and complete historical data on weather and crop yield. The amount of required data depends on the frequency of the risk to insure. Twenty years of data may be sufficient to set initial premium rates for relatively frequent weather events, while thirty or forty years of data may not be sufficient for infrequent but potentially catastrophic events (Barnett & Mahul, 2007; World Bank, 2010). The scarcity of these data entails model risk and additional premium loadings that make insurance unattractive to potential buyers, despite the huge demand for yield risk reduction (Odening & Shen, 2014). In many countries, weather data have public goods characteristics, they are unlikely to be collected, cleaned and archived. In addition, these data are not freely available, either as a result of restrictive use policies and fees being charged, or are of poor data coverage and quality. Consequently, data quality and access remain an important unresolved challenge in the implementation of weather index insurance at larger scale (Barnett *et al*., 2007).

Some of the suggested options to mitigate the problem of data scarcity include the use of daily observations of temperature and/or rainfall to construct a weather index or simulate synthetic yield-data series through plant-growth models for area-yield index (Dick *et al.* 2011; Odening & Shen, 2014). In Ethiopia, agronomist and weather experts developed the Livelihoods, Early Assessment and Protection (LEAP) software application which uses ground and satellite rainfall data to map the whole of Ethiopia with ability of covering areas without weather stations (Hazell *et al.* 2010). As reported by World Bank (2015), where both historical yield and weather data are not available, ACRE-Africa relied on satellite data and testing analysis techniques to generate the most accurate proxy for the farmer experience.

Capacity building of stakeholders

Index insurance is a complex concept which requires substantial investment in training of stakeholders along the implementation scheme (Miranda & Milangu, 2016). Particularly, potential policyholders need to understand the basic risk inherent with index insurance to make an informed purchase decision (World Bank, 2010). In Ethiopia, weather index insurance for famine prevention tested by World Bank and World Food Program (WFP) in 2005/2006 was later discontinued by farmers after one year with good rainfall. Farmers and policymakers were not sufficiently educated on how weather index insurance principles operate and become hesitant after a good harvest to pay for the insurance coverage in the next season (Tadesse *et al.*, 2015).

Therefore any rollout of the product requires intense education programs to strengthen them to understand the principles of the entire delivery system. To date, experience with capacity building and education of stakeholders has provided positive and convincing results (Barnett & Mahul, 2007).

While explaining the index insurance, McPeak *et al.* (2010) designed an illustrative and playing game through which pastoralists in Northern Kenya were able to understand how it works, what it does and does not cover. To successfully publicize an insurance product and prepare extension effort, Mude *et al.* (2010) suggested to train first master trainers (MT) followed by another training of Village Insurance Promoters (VIP) recruited from the targeted villages. Later, MTs and VIPs would continue offering their extension services towards selling insurance products to farmers. Following this approach, IBLI product was successfully sold to pastoralists in Marsabit district in Kenya (Chantarat, 2009). Dercon *et al.* (2014) reported that the demand and uptake for insurance products among trained policyholders increased when groups were exposed to training and other capacity building opportunities. While investigating the demand for insurance in Ethiopia, Dercon *et al.,* (2014) found a higher uptake among farmers who had heard about the insurance policy (22%) or trained (36%) against only 2% among those that were not trained.

Lack of innovation for local adaptation and scalability

While the insurers have shown considerable interest in selling index-based insurance products, their ability to innovate is limited. Until there is commercial success, there is little incentive for private companies to invest adequate time and resources in building internal capacity and funding experiments for setting up new models (FSD Kenya, 2013). However, on-going annual reviews of the trigger levels are advisable, especially in the first years of implementing an insurance program. The lack of this technical work limits the speed at which the scaling up of a pilot program to a regional or national levels (World Bank, 2010).

2.4.5. Opportunities for index-based insurance products

African Risk Capacity program (ARC), government and public sector support, use of mobile network operators, public-private partnership, and interlinking insurance with safety net programs are presented as opportunities to speed up the uptake of index-based agricultural insurance in SSA.

African Risk Capacity program

The African Risk Capacity (ARC) program is a specialized agency of the African Union (AU) designed to improve the capacity of African Union Member States to manage natural disaster risk, adapt to climate change and protect food insecure populations. As of February 2017, sixteen countries had signed the Memorandum of understanding with ARC. These countries include Malawi, Kenya, Niger, Lesotho, Senegal, Burkina Faso, Mozambique, Mauritania, Zimbabwe, Ghana, The Gambia, Mali, Comoros, Chad, Madagascar, and Ethiopia (ARC, 2016). Voluntarily, member states subscribe to the ARC risk pool and based on the WRSI calculations, Africa RiskView software estimates the number of people potentially affected by drought for each country participating in the insurance pool. Due to drought stress observed during 2014 and 2015 agricultural seasons, governments of Senegal and Malawi benefited from ARC a pay-out of USD 16 million, and 8.1 million, respectively (ARC, 2016). With support from the German and UK governments, ARC Ltd issued nearly $130 million in drought coverage to Kenya, Mauritania, Niger, Senegal, The Gambia, Malawi and Mali for the risk pool in 2014-2016 (ARC, 2016).

Government and public sector support

Governments and their regulatory agencies play a central role in properly positioning index insurance programs within the existing insurance and financial regulatory framework (Miranda & Milangu, 2016). Arshad *et al.* (2015) reported that governmentally subsidized crop insurance schemes are needed to attract the small farmers to purchase insurance contracts. However, the insurer should be financially responsible for its own affairs, free of government manipulation and not accessing government funds. If needed, subsidies should be set as some fixed percentage of the total premium. The insurance provider is more likely to succeed if it is an autonomous public institution with its own board of directors, and not a department within the Ministry of Agriculture (Hazell, 1992; World Bank, 2009).

Use of mobile network operators

The largest challenge in developing any financial product is its distribution, especially if the product is targeting to reach small-scale farmers. One of the solutions to this barrier is partnering with mobile network operators. Under "community based health insurance" in Rwanda and "mi-life" micro-insurance in Ghana, MTN subscribers were able to buy life insurance products, pay premiums and make claims through their mobile phones (World Bank, 2015).

Collaborating with Safaricom, the largest mobile network operator in Kenya, ACRE Africa sold its insurance products to over 390,000 farmers in Kenya and Rwanda, by the end of 2015 (World Bank, 2015; Tadesse *et al*., 2015). In Ethiopia, M-Birr, a mobile money channel targeting rural residents, enabled almost 50,000 account holders to transfer, deposit or withdraw money without leaving the comfort of their homes (Mugambi, 2016). Initiated in 2015, the mobile money interoperability between different mobile network operators (MNOs) is also presented as a winning formula to increase insurance penetration within Africa (GSMA, 2015).

The interoperability will help to enhance the financial transaction among customers through sending money across mobile network operators. For example, in 2014, operators in Pakistan, Sri-Lanka and Tanzania interconnected their mobile money services, which allowed their customers to send money across networks within those countries (GSMA, 2015).

Public and private partnerships

The development of agricultural insurance markets requires public and private sectors to overcome institutional, technical and financial challenges (World Bank, 2010). For example in East Africa (Kenya, Tanzania and Rwanda), Agriculture and Climate Risk Enterprise (ACRE-Africa) is demonstrating positive development impact with index based crop insurance. ACRE recognizes the wide range of partners as a major reason behind their rapid scaling and demand. Partners include banks and micro-finance institutes (MFIs), mobile network operators, seed companies, government agencies, research institutions, insurance and reinsurance companies, and global donors like Global Index Insurance Fund "GIIF" (Greatrex *et al.*, 2015).

Interlinking weather index insurance with safety net programs

The Horn of Africa Risk Transfer and Adaptation project (HARITA) developed a more participatory weather index insurance product in Ethiopia. Through the creation of employment opportunities, HARITA project integrated the Productive Safety Nets Program (PSNP) activities of the Ethiopian government (tree planting or other public goods) with the so-called insurance for work (IFW) model (Bageant & Barrett, 2015). Resource-poor farmers were able to pay insurance premiums in kind and receive insurance certificate to guarantee pay-outs in the event of drought affecting crop production. This approach has been tested in northern Ethiopia by Oxfam America, and about 60 % of the households chose to participate in the insurance for work program to get coverage for their most important staple cereal crop, *teff*. In 2012, about 19,000 farmers were insured over 76 villages in northern parts of Ethiopia (Greatrex *et al*., 2015). This approach resolves the cash constraints of the poor to invest in risk transfer instruments and could contribute to enhancing wider uptake if the index is appropriate (Tadesse *et al*., 2015).

2.5. Crop simulation models

2.5.1. Rationale of crop simulation models

Traditionally, the relationship between crop yield and water supply has been based on empirical production functions, which cannot be extrapolated reliably beyond the location for which they were developed (Kumar *et al.*, 2017). Currently, crop simulation models are available and increasingly used to quantify the effects of environmental conditions and agricultural practices on crop performance (Foster *et al.*, 2017). One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. This provides the proper means to analyze the effects of the changes of soil characteristics or weather pattern separately, which is difficult to achieve in field experiments (Rezzoug *et al*., 2008; Singh, 2016). Some of the most used crop simulation models include computer based software package such as Decision Support System for Agro-technology Transfer (DSSAT), Cropping System Simulation Model (CropSyst), Aqua Crop Model, Agricultural Production System Simulator (APSIM), etc...

2.5.2. Decision Support System for Agro-technology Transfer

Decision Support System for Agro-technology Transfer (DSSAT) is an integrated computer system developed by International Benchmark Sites Network for Agro Technology (IBSNT). DSSAT model integrates various sub models (Figure 5) which include CERES- cereal model for maize, rice, sorghum, wheat, CROPGRO model for peanut, soybean and common bean, SUBSTOR model for cassava and potato and CROPSIM model for crops such as tomatoes (Eitzinger *et al.*, 2012). Its initial development was motivated by a need to integrate knowledge about soil, climate, crops and management for making better decisions about transferring production technology from one location to others where soils and climate differed.

It can be used to verify scientific hypotheses, simulate seasonal changes, spatial transformation and the effect of different management measures on the process of crop growth (Jones *et al.*, 2003). Particularly, DSSAT model can simulate mono-crop production systems considering weather, genetics, soil water, soil carbon and nitrogen, and management in single or multiple seasons and in crop rotations at any location where minimum inputs are provided.

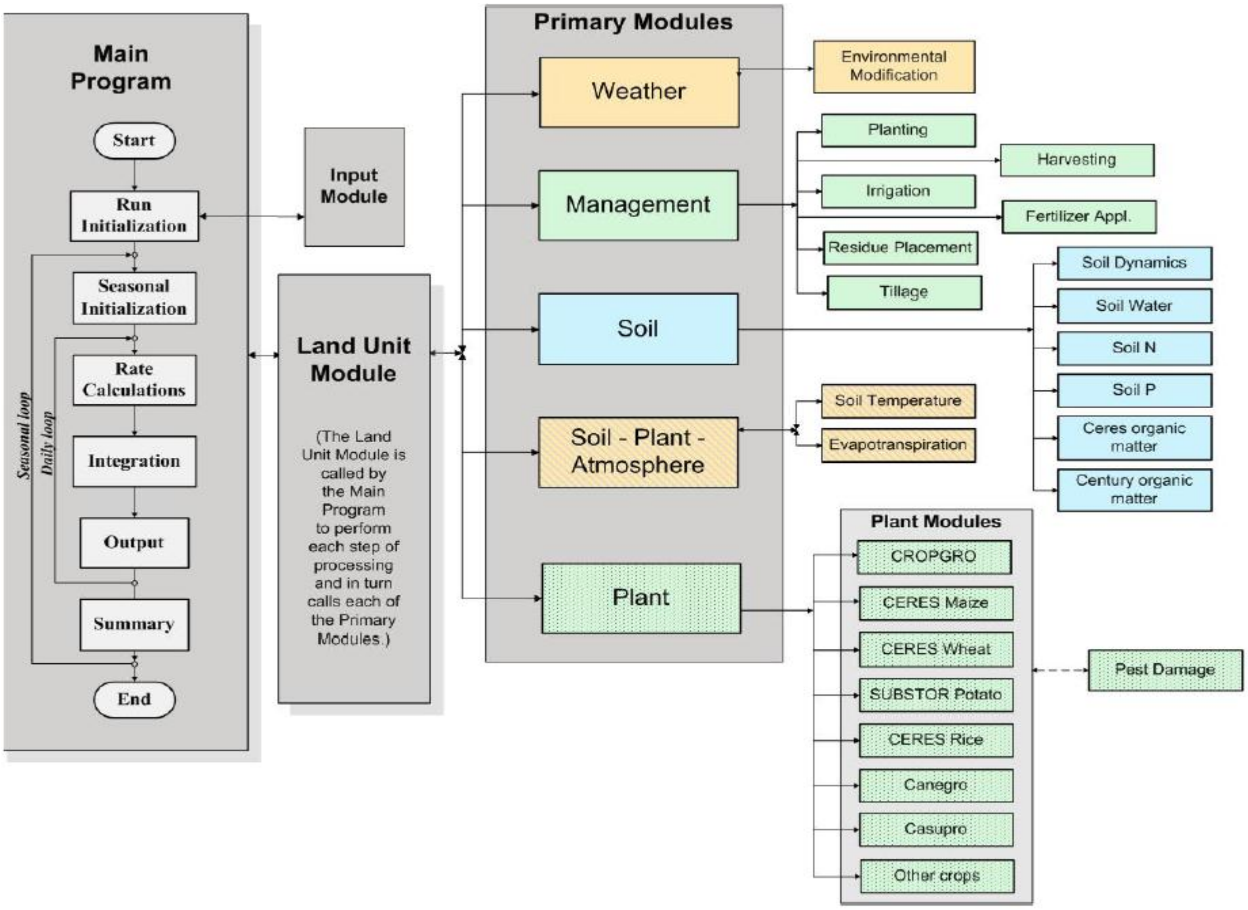


Figure 5: [2.4] Components and modular structure of DSSAT (Eitzinger *et al.*, 2012)

CHAPTER THREE

EFFECT OF EXCESSIVE AND MINIMAL SOIL MOISTURE STRESS ON AGRONOMIC PERFORMANCE OF BUSH AND CLIMBING BEAN (*PHASEOLUS VULGARIS*)

Abstract

Water stress is a major crop production constraint for common bean (*Phaseolus vulgaris).* The response of bush and climbing bean to excessive and minimal soil moisture at various plant growth stages was investigated under netted greenhouse experiment for two growing periods; September-February 2016 and March-July 2016. Two bean genotypes RWR2245 (bush bean) and MAC44 (climbing bean) were used for this study. The treatments consisted of three watering regimes namely minimal soil moisture stress, excessive soil moisture stress in addition to the control. The minimal soil moisture treatment (drought stress) consisted of withholding water supply, from the on-set of emergence, vegetative, flowering, pod setting and seed filling growth stages, up to the temporal wilting point of plants. The excessive soil moisture treatment (waterlogging stress) was achieved by saturating the soil on a daily basis for five successive days, starting from the on-set of the aforementioned plant growth stages. The control treatment consisted in watering with recommended rates for each plant growth stage. For each genotype, these treatments were replicated four times and arranged in a Completely Randomized Design (CRD). Drought stress accelerated the number of days to maturity whilst waterlogging stress tended to increase the number of days to maturity. Both stresses reduced the agronomic performance of both genotypes. However, pod setting and flowering were the most sensitive stages to drought stress and waterlogging stress, respectively.

Keywords: Crop development, Drought stress, Grain yield, *Phaseolus vulgaris*, Waterlogging

3.1. Introduction

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume and among staple food in East Africa. For instance in Burundi, Rwanda, Uganda and in Western Kenya, bean consumption is estimated at 60 kg per capita per year which is about thrice the mean for Africa (Ostyula, 2010; Buruchara *et al*., 2011; Beebe *et al*., 2013). However, due to various production constraints, availability and cost often limit bean consumption. Nutritionally, common bean has a high protein content with a good source of energy and it provides folic acid, dietary fibre and complex carbohydrates (Dagnew *et al*., 2014). In addition, common bean protein is high in lysine, which on the other hand is relatively deficient in maize, cassava and rice, making it a good dietary complement to these staples (Katungi *et al*., 2009). Given that most proteins consumed by the poor are from plant sources, common bean plays a significant role in alleviating malnutrition. Bean products are consumed at various stages of plant development, and thus, offer a staggered and prolonged food supply in the form of leaves, green pods, fresh grains, dry grains, as well as bean composite flour for porridge and other snacks.

Beyond promoting food, health and nutritional security, common bean provides a steady and lucrative source of income for many rural households in Eastern and Southern Africa, with the value of bean sales exceeding US $ 500 million annually (FAO, 2011; Kalima, 2013). In Zambia for instance, common bean is one of the major sources of income for the smallholder farmers especially women (Samboko *et al.*, 2011).

Despite the importance of common bean in food security and nutrition, production of the crop is limited due to biotic and abiotic stresses (Dagnew *et al*., 2014). In most African countries, the bean crop is grown by smallholder farmers under rain-fed conditions and increasingly subjected to unreliable dry and/or wet weather conditions. Therefore, water stress is a very common problem during the growing period and often aggravated by the declining soil fertility, diseases, limited access to improved seeds and suboptimal agronomic practices (Calvache *et al*., 1997; Polania *et al*., 2016).

On one hand, drought is a major constraint to bean production and its mode of action is highly complex and variable in response, accentuated by interacting factors and localized within environmental regions (Dagnew *et al*., 2014). According to Polania *et al.* (2016), drought is the second most important factor in yield reduction after diseases. Brief periods of water shortage impose a stressful metabolic situation by particularly altering plant photosynthesis, which leads to a depletion of energy and sugars and negatively affect both quality and yield of beans (Cuellar-Ortiz *et al.*, 2008). Adaptation to drought stress encompasses morphological, physiological, and biochemical mechanisms, including a deeper root system, stomatal control, and improved photosynthate remobilization under stress (Beebe *et al.*, 2011).

On the other hand, excessive rainfall often exposes plants to transient or permanent waterlogging stress, particularly in tropical and subtropical regions. In waterlogged soils, gas exchange between root systems and soil pore spaces are limited due to oxygen diffusion resistance that is around 10,000 times higher in water than in the air (Ashraf, 2012; Borella *et al*., 2014). Since oxygen diffuses through undisturbed water much more slowly than a well-drained soil, when soils are saturated, oxygen requirements rapidly exceed available concentrations (Meronuck *et al*., 2016). As a result, plant roots suffer from hypoxia (deficiency of O_2) or anoxia (absence of O_2), which reduce nutrient uptake, crop growth and yield (Houk *et al*., 2004; Ashraf, 2012). Crop damages due to waterlogging include necrosis, stunting, defoliation, reduced nitrogen fixation and plant death (Ahmed *et al*., 2013). In addition to the effect on the roots, excessive rainfall does have destructive effects on plant leaves. A number of foliar diseases such as common bacterial blight, halo blight, angular leaf spot and bean anthracnose are prominent in periods of wet weather resulting in loss in photosynthetic area which can affect final yield (Mukankusi *et al.,* 2008; Buruchara *et al*., 2010; Cyamweshi *et al.,* 2013). Only two days of flooding at vegetative stage can cause 18 % of yield loss while it may exceed to 26% if flooding occurs at early reproductive stage of soybean (Ahmed *et al.,* 2013). As indicated by Beebe *et al.* (2011) and Li *et al.* (2015), in common bean, no variety to date has been identified with resistance to waterlogging. However, farmers in Uganda and Rwanda substitute bush bean genotypes with climbing bean type which cope better with waterlogging stress (Cyamweshi *et al.,* 2013).

Although many studies have been carried out on the effect of drought stress, at particular stages of bean crop development, few studies are related to assessment of excessive moisture stress at the various developmental stages of the common bean.

The main objective of this study was therefore to determine the most sensitive stages of bean growth to water stresses and their impact on yield of two common bean genotypes (MAC44 and RWR2245) with different growth habits grown under greenhouse conditions. These two genotypes are regionally recognized for their high yield potential and have been recently released as varieties in Rwanda, Burundi, and pre-released in Kenya (Mutoni & Andrade, 2015). They are recommended for low and medium altitudes and have yield potentials of 2.5 t ha^{-1} for RWR2245 (bush type) and of 3.5 t ha^{-1} for MAC44 (climbing type). Because of their high yield potential, farmers have rapidly adopted these varieties as grain yield is the most desired character of farmer’s interest in field crops and considered as the economic outcome of farming (Ahmed *et al.,* 2015).

Particularly, in Rwanda and Burundi, where climbing bean varieties are being intensively adopted, MAC44 has appeared as an alternative solution to bean production under scarcity of arable land (Katungi *et al*., 2009). Specifically, this study aimed at assessing the effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean types. The expected outcome from this study is that the information generated would contribute to develop possible agronomic and insurance packages to confront variations in rainfall and sustain bean production that are beneficial to smallholder farmers, particularly in developing countries.

3.2. Materials and Methods

3.2.1. Location and plant materials

The study was conducted under greenhouse conditions for two growing periods: September - February 2016 and March - July 2016. The first growing period was carried out in Kenya at Kabete Field Station of the University of Nairobi (elevation: 1850 masl) and the second in Rwanda at Rubona Research Station (elevation: 1650 masl) of Rwanda Agriculture Board (RAB). In order to assess the effect of water stresses on the performance of both bush and climbing beans, two improved bean genotypes namely MAC44 (climbing bean) and RWR2245 (bush bean) were used. Major characteristics of the two genotypes selected for the study are listed in Table 5.

Table 5: [3.1] Major characteristics of the two bean genotypes selected for the study

Attributes	MAC44	RWR2245
Growth habit	Climbing (type IV)	Bush (type I)
Adaptation zone	Low and medium altitude	Low and medium altitude
Days to maturity	87	78
Potential yield, kg ha^{-1}	3,500	2,500
Iron content, mg kg^{-1}	78	75
Zinc content, mg kg^{-1}	29	29.8
Seed size	Large	Medium
Color	Red mottled	Red mottled
Disease, tolerance/resistance	Angular leaf spot, Ascochyta, Root rot, Anthracnose, Bean common mosaic virus	Angular leaf spot, Ascochyta, Root rot, Anthracnose, Bean common mosaic virus

Adapted from Musoni *et al.*, 2012

3.2.2. Experimental design and treatments

The evaluated treatments were three watering regimes namely minimal/moderate watering (drought stress), excessive watering (waterlogging stress) and normal watering (control), applied at the on-set of the five plant growth stages i.e. emergence, vegetative, flowering, pod setting and seed filling. These treatments were initiated at the two primary leaves unfolded for emergence stage, the fourth trifoliate leaf unfolded for vegetative stage, at one open flower for flowering, at early pod set for pod setting and at early seed fill for seed filling stage. Each treatment was replicated four times and pots were arranged in a Completely Randomized Design (CRD). The combination of these soil moisture levels with plant growth stages resulted in eleven treatments (Table 6).

Table 6: [3.2] Description of treatments

Growth stages	Water stress	Treatments	Treatment description
Emergence	Drought stress	DS-E	Stop watering from the two primary leaves unfolded (VC) until the plants temporally wilt
	Waterlogging stress	WL-E	Keep soil water content at saturation for five successive days from the two primary leaves unfolded
Vegetative	Drought stress	DS-V	Stop watering from the 4th trifoliate leaf unfolded (V4) until the plants temporally wilt
	Waterlogging stress	WL-V	Keep soil water content at saturation for five successive days from the 4th trifoliate leaf unfolded
Flowering	Drought stress	DS-F	Stop watering from early flower stage (R1) until the plants temporally wilt
	Waterlogging stress	WL-F	Keep soil water content at saturation for five successive days from early flower stage
Pod setting	Drought stress	DS-P	Stop watering from early pod set (R3) until the plants temporally wilt
	Waterlogging stress	WL-P	Keep soil water content at saturation for five successive days from early pod set stage
Seed filling	Drought stress	DS-S	Stop watering from early seed fill (R5) until the plants temporally wilt
	Waterlogging stress	WL-S	Keep soil water content at saturation for five successive days
Throughout all the plant growth stages	Normal watering	Control	Watering with recommended rates of 2, 3, 6, 7, and 7 mm day^{-1} at vegetative, flowering, pod development and seed filling, respectively (Beebe *et al.*, 2013; Meronuck *et al.*, 2016)

The drought stress treatment consisted of withholding water supply until the plant reaches temporal wilting. The treatment was initiated at the two primary leaves unfolded for emergence stage, at the fourth trifoliate leaf unfolded (V4) for vegetative, at one open flower (R1) for flowering, at early pod set (R3) for pod setting and at early seed fill (R5) for seed filling stage.

Waterlogging stress was applied by always keeping the soil water content above 40% and 35% of volumetric water content for clay and sandy-soil, respectively (Sheppard and Hoyle, 2016). This was achieved by saturating the soil on a daily basis for five successive days, starting from the two primary leaves unfolded for emergence stage, from the fourth trifoliate leaf unfolded (V4) for vegetative stage, from one open flower (R1) for flowering stage, from early pod set (R3) for pod setting stage and from early seed fill (R5) for seed filling stage. The control treatment was applied by watering each pot with an equivalent of 2 mm day^{-1} at emergence, 3 mm day^{-1} at vegetative, 6 mm day^{-1} at flowering, 7 mm day^{-1} at pod setting and 7 mm day^{-1}at seed filling, as recommended by Meronuck *et al*. (2016). Before and after the water stress treatments were applied, the pots received recommended watering rates based on the plant growth stages (Table 7). During the late seed filling, watering was stopped as it is known to promote more vegetative growth at the expense of reproductive growth in common bean (Beebe *et al*., 2013).

Table 7: [3.3] Estimated daily rates of water per growth stage for normal dry bean irrigation

Plant growth stages	Recommended rates		Pot area	Applied rates	
	mm day^{-1}	L m^{-2}	m^{2}	L pot^{-1}	mL pot^{-1}
Emergence	2	2	0.0314	0.0628	65
Vegetative	3	3		0.0942	100
Flowering	6	6		0.1884	190
Pod development	7	7		0.2198	220
Seed filling	7	7		0.2198	220
Physiological maturity	3	3		0.0942	100
Leaves yellowing	1	1		0.0314	35

Adapted from Meronuck *et al*., 2016

Throughout this experiment, water stress treatments were applied by monitoring soil moisture content, using a capacitance probe (ProCheck PC-1 with GS sensor 2007-2014 Decagon Devices).

3.2.3. Growth conditions and greenhouse management

The experimental unit was a five litre capacity pot filled with 4 kg of top soil. The characteristics (soil texture and fertility status) of the soils used in this experiment (Table 8) were clay (Sep – Feb 2016) and sandy-clay (Mar – Jul 2016) soils in texture, low P, moderately acidic, moderate in total N, very low (Sep –Feb 2016) and Medium in Organic Carbon (Horneck *et al*., 2011).

Table 8: [3.4] Selected physical and chemical characteristics of experimental soils

Site (season)	Clay (%)	Sand (%)	Silt (%)	pH	Bray P (ppm)	Total N (g kg-1)	Total C (g kg-1)
Kabete (Sep-Feb)	59	23	18	5.0	1	1.6	18
Rubona (Mar-Jul)	36	54	10	5.5	10	1.8	40

Planting was done at seedling rate of two seeds per pot and thinned to one plant per pot after emergence (at two primary leaves unfolded). Each experimental pot was fertilized with a pre-planting dose of Urea (23 kg ha^{-1}) and TSP (46 kg ha^{-1}), in addition to organic manure (10 t ha^{-1}). During the experimental period, pots were kept free from weeds, pests and diseases by a combination of hand weeding, use of insecticide (Cypermethrin 5% EC) for insect control and fungicide (Safari-Zeb 80WP) for fungal diseases control. These pesticides were applied every seven to ten days at a rate of 25 mg L^{-1} of water (spray volume of 1,000 - 2,000 L ha^{-1}) for Cypermethrin (insecticide) and 2.5 g L^{-1} of water (spray volume of 500 - 1,000 L ha^{-1}) for Agro-Zeb 80WP (fungicide). In addition, pots were rotated every three to five days to minimize possible location effect on plant development. Woody stakes of 2.5 m height were used for staking climbing bean genotype (MAC44).

3.2.4. Data collection and analysis

Data on plant phenology (days to flowering, plant height and days to maturity), number of pods per plant, number of grains per pod, weight of 100 grains, and grain yield per pot were recorded. These data were subjected to analysis of variance (ANOVA) using GenStat 14th Edition (VSN International, 2011). Mean differences among water stress treatments were determined according to the Tukey's Honest Significant Difference method. The rate of yield decrease due to water stress treatments was estimated using the formula:

$$Y_D = 100\ x \left[\frac{Y_C\ -\ Y_T}{Y_C}\right]$$

Where: Y_D is the percentage of grain yield decrease; Y_C is the average yield obtained under the control "C"; and Y_T is the average yield obtained under the treatment "T"

3.3. Results

The present study showed that drought and waterlogging stresses had negative effect on plant growth and grain yield components of bush and climbing beans (Table 9 and Table 10).

Table 9: [3.5] Effect of drought and waterlogging stress on growth and yield of RWR2245 (bush type)

Treatments†	Days to flowering	Days to p.maturity	Plant height (cm)	Pods/plant (number)	Grains/pod (number)	100-grains weight (g)	Yield (g/plant)
Control	38^{ab}	69^{bc}	53^{a}	23^{a}	4^{a}	50^{a}	21^{a}
DS-E	35^{b}	64^{d}	46^{ab}	20^{a}	3^{ab}	46^{abc}	18^{ab}
DS-V	39^{a}	65^{d}	44^{ab}	11^{bc}	3^{ab}	41^{abc}	18^{ab}
DS-F	38^{a}	66^{cd}	47^{ab}	10^{c}	3^{ab}	42^{abc}	17^{ab}
DS-P	38^{a}	64^{d}	49^{ab}	10^{c}	3^{ab}	42^{abc}	17^{ab}
DS-S	38^{a}	67^{d}	49^{ab}	11^{bc}	3^{ab}	41^{abc}	18^{ab}
WL-E	38^{a}	74^{a}	50^{ab}	16^{ab}	4^{a}	49^{ab}	16^{ab}
WL-V	39^{a}	72^{ab}	43^{b}	11^{bc}	3^{ab}	37^{c}	14^{b}
WL-F	39^{a}	68^{bcd}	48^{ab}	11^{bc}	3^{b}	41^{abc}	13^{b}
WL-P	38^{a}	69^{bc}	52^{ab}	11^{bc}	3^{ab}	42^{abc}	19^{ab}
WL-S	37^{ab}	70^{bc}	49^{ab}	12^{bc}	3^{ab}	39^{bc}	18^{ab}
P-value	<0.001	<0.001	0.024	<0.001	0.013	0.003	0.008
Significance‡	(***)	(***)	(*)	(***)	(*)	(**)	(**)
CV (%)	3.3	3.7	11.5	25.1	16.7	15.3	21.8

Mean treatments estimated from n= 8 plants per treatment, Within the same column, values that differ according to analysis of variance ($p \leq 0.05$) and Tukey's Honest Significant Difference Method are marked with different small letters;
‡: (ns) = no significant; (*), (**), (***) = significant at 0.05, 0.01 and 0.001, respectively (F test)
†: DS=Drought stress, WL=Waterlogging stress, E=Emergence, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling

Table 10: [3.6] Effect of drought and waterlogging stress on growth and yield of MAC44 (climbing type)

Treatments†	Days to flowering	Days to P.maturity	Plant height (cm)	Pods/plant (number)	Grains/pod (number)	100-grains weight (g)	Yield (g/plant)
Control	43^{b}	83^{bc}	166	13	5^{ab}	63^{a}	24^{a}
DS-E	45^{ab}	78^{d}	150	10	5^{ab}	51^{ab}	23^{ab}
DS-V	44^{b}	79^{d}	149	9	4^{bc}	63^{a}	20^{abc}
DS-F	43^{b}	80^{cd}	147	11	4^{bc}	55^{ab}	21^{abc}
DS-P	42^{b}	80^{cd}	168	9	3^{c}	60^{a}	14^{bc}
DS-S	42^{b}	79^{d}	154	10	3^{c}	55^{ab}	18^{abc}
WL-E	48^{a}	87^{ab}	155	9	5^{a}	50^{ab}	19^{abc}
WL-V	43^{b}	88^{a}	148	9	4^{abc}	52^{ab}	16^{abc}
WL-F	44^{b}	86^{ab}	144	9	3^{c}	45^{b}	14^{c}
WL-P	43^{b}	86^{ab}	169	10	4^{bc}	58^{ab}	18^{abc}
WL-S	43^{b}	86^{ab}	165	8	4^{bc}	46^{b}	18^{abc}
P-value	<0.001	<0.001	0.579	0.603	<0.001	0.028	0.003
Significance‡	(***)	(***)	(ns)	(ns)	(***)	(*)	(**)
CV (%)	4.8	3.1	18.2	42.9	21.3	21.6	27.8

Mean treatments estimated from n= 8 plants per treatment, Within the same column, values that differ according to analysis of variance ($p \leq 0.05$) and Tukey's Honest Significant Difference Method are marked with different small letters;
‡: (ns) = no significant; (*), (**), (***) = significant at 0.05, 0.01 and 0.001, respectively (F test)
†: DS=Drought stress, WL=Waterlogging stress, E=Emergence, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling

3.3.1. Number of days to flowering and physiological maturity

For both bush and climbing bean genotypes, water stress levels had a highly significant effect on the number of days from sowing to flowering ($P< 0.001$) and physiological maturity ($P< 0.001$). The drought stress at late stages of plant growth (pod setting and seed filling) accelerated the physiological maturity by 4 days on average. Whereas, waterlogging stress at early plant growth stages (emergence, vegetative) prolonged days to physiological maturity by 4 days on average for bush and climbing beans (Table 9 and Table 10).

3.3.2. Plant height

Water stress treatments had a significant effect on plant height for bush bean ($P = 0.024$) and not no significant for climbing bean ($P=0.579$). Drought stress and waterlogging stress at the evaluated developmental stages reduced plant height for both bush and climbing bean genotypes (Table 9 and Table 10). Higher reductions of pant height were observed under drought and waterlogging stress at vegetative and flowering stages. However, the shortest plants were observed for waterlogging stress at vegetative stage for bush bean (43 cm) and at flowering for climbing bean (144 cm).

3.3.3. Number of pods per plant and number of grains per pod

For both bush and climbing bean genotypes, water stress levels had a significant effect on the number of grains per pod. For climbing bean, no significant effect was observed in the number of pods per plant with water stress treatments, although a decrease was noticed for all treatment levels (Table 9 and Table 10). For bush and climbing bean genotypes, the small numbers of grains per pod was observed under drought stress at pod setting and under waterlogging stress at flowering. The lowest number of grains per pod was obtained under waterlogging stress at flowering stage.

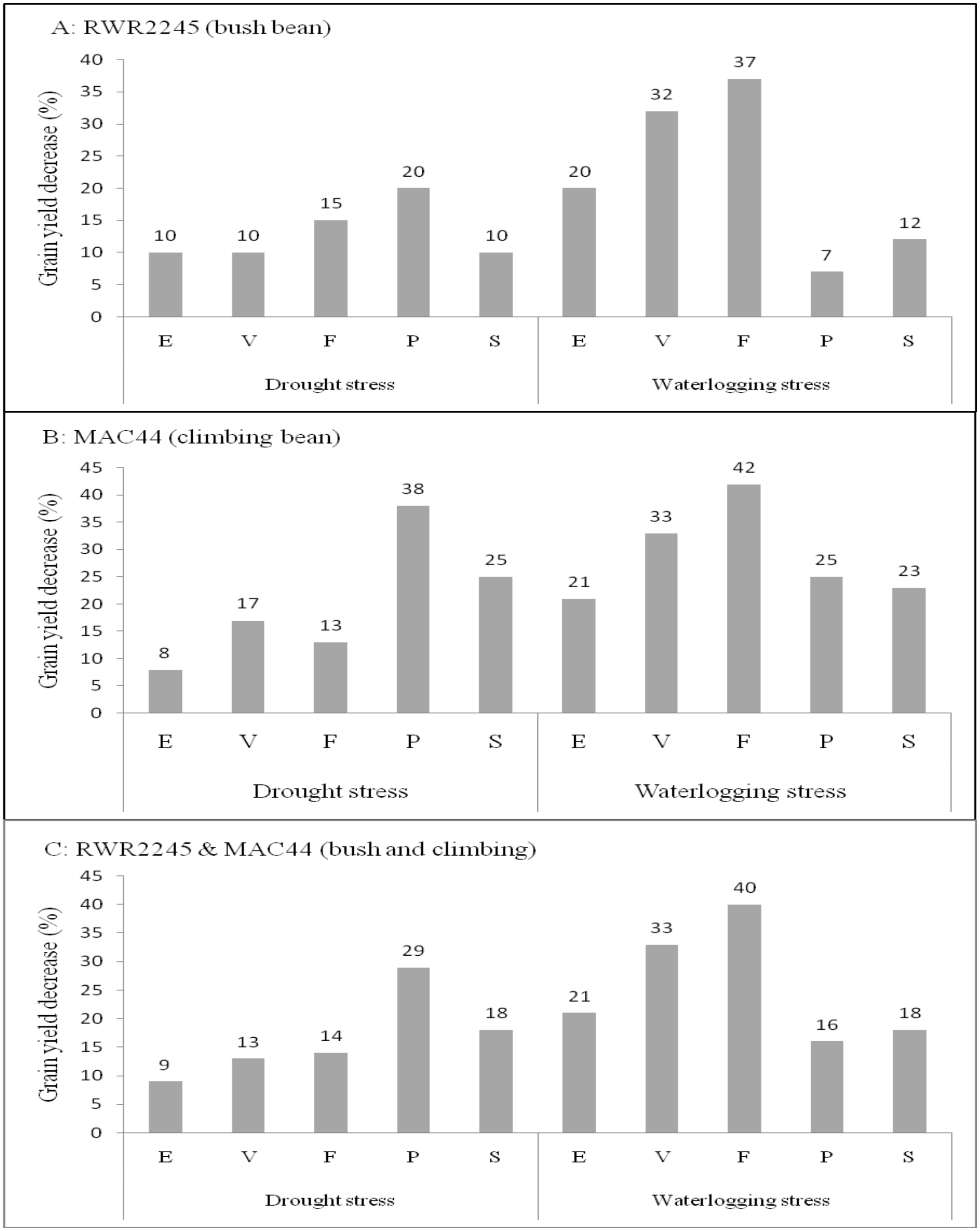
3.3.4. Weight of 100 grains

Compared to the control (unstressed treatment), water stress conditions reduced weight of 100 grains in both cultivars significantly (Table 9 and Table 10). The weight reduction was higher for waterlogging stress during vegetative for bush beans and seed filling for climbing bean. However, the lowest weight of 100 grains was observed for waterlogging stress at vegetative for bush bean and waterlogging stress at flowering and seed filling for climbing bean.

3.3.5. Grain yield

Highly significant differences were observed among water stress treatments for grain yield of both bush bean and climbing bean (Table 9, Table 10). For bush bean, the lowest grain yield was obtained under waterlogging stress at flowering stage and estimated at 13 and 14 g pot^{-1} for bush and climbing bean, respectively.

Water stress levels caused a reduction in grain yield in both cultivars as compared to the non-stressed treatment (Figure 6). Drought and waterlogging stress conditions appeared to have stronger effect on the grain yield of climbing bean than bush bean. Compared to the non-stressed treatment, waterlogging stress reduced grain yield by, on average, 22% and 29%, for bush and climbing bean, respectively. Whereas, drought stress reduced grain yield on average of 13%for bush bean and 20% for climbing bean. For both genotypes, pod setting and flowering stages were respectively most sensitive to drought and waterlogging, causing a yield reduction of 29% and 40% (Figure 6). In contrast, both genotypes showed a better ability to recover from stress at emergence and vegetative stages than at reproductive stages.



A: RWR2245 (bush bean)

B: MAC44 (climbing bean)

C: RWR2245 & MAC44 (bush and climbing)

E=Emergence, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling

Figure 6: [3.1] Effect of water stress at different growth stages on bean yield decrease

3.4. Discussion

3.4.1. Days to physiological maturity

Significant reduction in days to physiological maturity as a result of water stress (drought stress) was observed in the present study which is consistent with previous reports (Muñoz-Perea *et al*., 2007; Beebe *et al*., 2008; Darkwa *et al*., 2016). As reported by Acosta-Diaz *et al*. (2009), most plant species have a tendency to escape from the effects of drought through a faster development in response to drought stress. Similar effects of drought stress on plant phenotype have previously been observed (Ramírez-Vallejo & Kelly, 1998). Therefore, the matching of crop phenotype to environmental conditions, mainly rainfall pattern, has been recognized as an important criterion for improving drought adaptation in common bean (Acosta-Diaz *et al.*, 2009). Waterlogging stress is also known to induce alterations in physiological mechanisms and cause adverse effects on several physiological and biochemical process of plants, due to the deficiency of essential nutrients like nitrogen, magnesium, potassium, and calcium (Ashraf, 2012). In addition, plants exposed to waterlogging stress exhibit stomatal closure, limited water uptake, oxygen deficiency and substantial decline of photosynthetic rate (Ashraf, 2012). Reduction of photosynthetic capacity of plants under waterlogged conditions has been reported in different plant species by a number of researchers, for example, *Lolium perenne* (McFarlane *et al*., 2003), *Lycopersicon esculentum* (Bradford, 1983; Jackson,1990) *Pisum sativum* (Zhang & Davies, 1987) and *Triticum aestivum* (Trought & Drew, 1980).

3.4.2. Plant height

Drought and waterlogging stress reduced plant height for evaluated treatment combinations. The plant height decrease was of high magnitude for drought or waterlogging stress at vegetative and flowering stages. The decreased plant height induced by water stress in the young plants could be due to the reduction in plant water status which reduces shoot elongation and leaf expansion together with reduced photosynthesis activity that leads to the inhibition of the plant growth. Extreme moisture stress reduces the ability of plant to utilize soil nutrients and causes reduction in growth rate as well as changes in plant metabolic processes. This finding is in line with Ahmed *et al*. (2015) and Amri *et al.* (2015) who reported that plant height, one of the indirect measures of the health of plants, is susceptible to environmental stresses occurred in early plant developmental phases. Similar results were found by Uddin *et al*. (2013) who reported plant height decrease for mungbean crop grown under minimal soil moisture stress (no irrigation) and plant height increase with no soil moisture stress (increased number of irrigations). The decrease was attributed to the inhibition of cell division or cell enlargement under soil moisture stress. Barrios *et al.* (2005) reported limited vegetative growth of grain legume crops, when soil moisture reaches the lower (or above) values of required available water.

3.4.3. Yield components

Yield components are generally good indicators of evaluating crop performance under defined growing conditions. The present study showed significant reductions in number of grains per pod, 100 grains weight, and grain yield under drought and waterlogged conditions. Similarly, Asfaw & Blair (2014) reported significant reductions in pod number per plant, seed number per pod, 100 seed weight and seed yield of common beans under similar drought-stressed conditions. The results from this study indicate that vegetative and flowering growth stages are relatively more sensitive to waterlogging stress whilst pod setting and seed filling stages are more sensitive to drought stress. These results are consistent with the findings of Ambachew *et al*. (2015) and Darkwa *et al*. (2016) who reported late flowering and pod setting stages to be the most sensitive stages to soil moisture stress. Likewise, Liu *et al.* 2007 reported that early seed development is extremely vulnerable to drought stress, mainly because it involves several processes that are highly sensitive to changes in plant water status. According to Emam *et al*. (2010) and Miorini & Saad (2012), the reduction of grain yield in water stress as compared to the non-stress condition, may have been attributed to a lower percentage of pods formed due to flower abscission and embryo abortion when drought occurred at flowering and pod filling growth stages. While investigating drought stress and the distribution of vegetative and reproductive traits of a common bean cultivar, Barrios *et al.* (2005) indicated that total number of flowers in some varieties may be reduced up to 47% under drought conditions affecting the number of pods per plant. In addition, Hossain *et al*. (2010) and Uddin *et al*. (2013), in their studies on Mungbean (*Vigna radiata L.*) indicated that the percentage of flower and pod abscission increased with increase in soil moisture stress.

Waterlogging is more common and often causes considerable yield loss across plant species. According to Riche (2004) waterlogging stress can reduce soybean yield up to 43% during the vegetative growth stages and 56% during the reproductive stage. Waterlogging during vegetative (V2) and early reproductive (R1 to R3) stages is more damaging to grain yield than other stages (Toai *et al.*, 2010). These yield losses are attributed to the reduced growth rate, reduced nutrient uptake, decrease of photosynthetic activity and incidence of diseases. There are a number of diseases that can take advantage of the wet conditions including *Phythophthora, Rhizoctinia, and Pythium*, among others (Scott *et al.*, 1989).

This study has positive implications for bean production in terms of both irrigation management and mitigation of the impacts of environmental stresses. Nowadays, deficit (or regulated deficit) irrigation is one way of maximizing water use efficiency for higher yields per unit of irrigation water applied (Bekele & Tilahun, 2007; Sadeghipour, 2008). Based on the results from the present study, deficit irrigation strategy may focus on withholding water supply at early plant growth stages (emergence, vegetative) of common bean. As confirmed by Sadeghipour (2008), water stress during certain growth stages may have more effect on grain yield than similar stress at other growth stages.

3.5. Conclusions

Drought and waterlogging stresses are among rapidly increasing constraints to agricultural production particularly for short season grain legume crops such as common bean. Drought and waterlogging treatments reduced common bean yield regardless of whether the stress was applied in the vegetative or in the reproductive stage of plant development. Days to flowering, days to physiological maturity, plant height, number of grains per pod, weight of 100 grains and grain yield were highly sensitive to water stresses. Plant height and number of pods per plant were the least sensitive parameters to waterlogging and drought stresses. Grain yield reductions were higher for drought stress at pod setting stage and for waterlogging stress at vegetative and flowering stages. Drought and waterlogging affected more severely pod developmental stage (pod setting and seed filling) and vegetative stage (pre-and early flowering), respectively. Based on the results from this study, for common bean, early plant growth stages (vegetative and flowering) are relatively more sensitive to waterlogging stress conditions whereas pod formation stage is most sensitive to drought-stressed conditions. To maximize bean production in dry areas, over-irrigation should be avoided at vegetative-flowering stages and normal irrigation extended across all phenological stages, especially during flowering, pod setting and seed filling stages of common bean.

CHAPTER FOUR

EFFECT OF NATURAL BEAN DISEASE PRESSURE ON YIELD LOSS OF COMMON BEAN (*PHASEOLUS VULGARIS*) IN LOW, MEDIUM AND HIGH ALTITUDE OF RWANDA

Abstract

Two field experiments were conducted for the period February 2016 to January 2017, to quantify the amount of yield losses due to natural bean disease pressure and investigate the relationships between disease and yield of common bean. Four bean genotypes (Akararakagenda, RWR2245, MAC44 and RWV1129) were exposed to the natural bean disease pressure through an open field experiment in low, medium and high altitude of Rwanda. The experiment was laid out in a split-split-plot design where the four bean genotypes were assigned to the whole plots, plant growth stages with four levels (vegetative, flowering, pod setting and seed filling) to sub-plots and pesticide application with two levels (application and no application) to the sub-sub-plots. The sprayed plots were treated with both Agro-Zeb 80WP (fungicide) at a rate of 2.5 g L^{-1} of water (spray volume of 500 - 1,000 L ha^{-1}) and Cypermethrin (insecticide) at a rate of 25 mg L^{-1} of water (spray volume of 1,000 - 2,000 L ha^{-1}). In all plots, natural infections of common bean by Angular Leaf Spot (ALS), Bean Common Mosaic Virus (BCMV), Ascochyta blight (ASCO) and Common Bacterial Blight (CBB) were observed. The maximum disease severities for ALS, CBB, BCMV and ASCO were, respectively, 6.8%, 0.6%, 2.8% and 6.6%. As expected, the plots that did not receive the treatment had higher bean disease severities than the corresponding treated plots. Yield losses due to natural bean disease pressure are higher (21%) for no pesticide application at pod setting stage. A linear regression model relating grain yield to bean diseases severities indicated that for each percentage increase in severity of ALS and BCMV there was a grain yield loss of 0.9% and 1.1%, respectively. Applying bean disease management measures at flowering and pod setting stages may be more appropriate and required for optimizing crop yield.

Keywords: Bean disease pressure, Grain yield, Growth stages, Pesticide, *Phaseolus vulgaris*

4.1. Introduction

Common bean (*Phaseolus vulgaris* L.) is essentially and widely cultivated for its significant source of dietary protein, consumed wholly without processing compared to other staple crops (Dhamulira *et al.*, 2014, Broughton *et al.*, 2003). Often grown and traded by women in Africa, common bean has increased wealth creation by female members of African communities with particularly a strong positive impact on food security, nutrition, child health, and school attendance rates (Kevane, 2012). For instance, in the Rwandan diet, dry beans provide 32 and 65 percent of calories and protein intake, whereas protein sourced from animal provides only 4 percent of the protein intake (CIAT, 2004; Asare-Marfo, *et al.,* 2013; Larochelle & Alwang 2014). Common bean is the second most popular crop (after banana) cultivated in Rwanda. In all the 30 districts of the Country, dry beans are grown by 95% of farmers two seasons a year, often intercropped with banana, cassava, maize, peas and other crops (Larochelle *et al.,* 2016). While climbing bean cultivation is most common in regions characterized by high elevation and heavy rainfall, bush beans are most preferred in low and mid land conditions with low or moderate rainfall (Sperling & Munyaneza, 1995; Larochelle *et al.* 2016). The widespread adoption of high yielding varieties, along with the shift from bush to climbing beans, has moved Rwanda from a position of net importer to self-sufficiency, and now to being an exporter of dry beans. Although staking materials remain a major challenge particularly in eastern province, where climbing beans are newly introduced before intensifying agro-forestry options (Mudingu, 2017).

Despite being of nutritional and economic value, common bean production is constrained by several biotic and abiotic stresses such as pests and diseases, low soil fertility, water stresses and poor crop management (Hillocks *et al*., 2006; Mwang’ombe *et al.,* 2007; Chilagane *et al.,* 2013).

In most African countries, bean production is not currently meeting demand and yields are very low. In Rwanda, farmers harvest around 500 kg ha^{-1} while the potential yield of common bean is of 4.5 t ha^{-1} for climbing bean type and 2.5 t ha^{-1} for bush type (Verdoodt *et al.,* 2004; Worrall *et al*., 2015; Larochelle *et al*., 2016). According to CIAT (2004) and Mudingu (2017), the most important diseases that affect dry bean production in Rwanda include angular leaf spot (ALS), bean anthracnose, Ascochyta blight and Bean common mosaic virus (BCMV). In the absence of adequate disease control measures, yield losses due to these biotic stresses can be as high as 50% for fungal diseases and 95% for viral diseases depending on the cultivar susceptibility and time of infection (Mavric & Sustar-Vozlic 2004; Hillocks *et al*., 2006; Tryphone *et al*., 2012; Chilagane *et al*. 2013). Whereas there is information on the occurrence, severity and yield losses due to some specific bean diseases, there is limited knowledge on losses due to the simultaneous occurrence of two or more disease on common bean (Pamela *et al.*, 2014). Usually the effects of a disease complex on yield are estimated by assuming that each disease acts independently (De Jesus Junior, 2001). However, the simultaneous occurrence of diseases can lead to combined effects on crop yield (De Jesus Junior, 2001; Pamela *et al*., 2014). In addition, establishing the relationship between disease incidence at different plant growth stages and subsequent yield loss is needed for decision making on alternative pest control strategies.

Therefore, this study was conducted with the objectives of (1) quantifying yield losses due to natural bean disease pressure on common bean in Rwanda, (2) characterizing the most important diseases and most susceptible plant growth stages to consider in developing an effective strategy for bean disease management and (3) assessing the relationship between observed bean disease and yield loss of common bean.

4.2. Materials and Methods

4.2.1. Experimental sites

Through on-farm and farmer participatory approaches, field experiments were conducted in Musanze (high altitude with high rainfall), Huye (medium altitude with moderate rainfall) and Bugesera (low altitude with low rainfall) districts, representing the diverse conditions under which beans are produced in Rwanda (Figure 7) for two successive cropping seasons: February to June 2016 and September-January 2017.

Figure 7: [4.1] Location of study sites

Weather conditions

During experimentation, the bimodal rainfall distribution was observed with abundant rainfall during March-April, moderate rainfall during (Sep-Nov) with drought spells in October for Bugesera and Huye Districts (Figure 8). The total annual rainfall observed were 648 mm for Bugesera, 935 mm for Huye and 1,222 mm for Musanze.

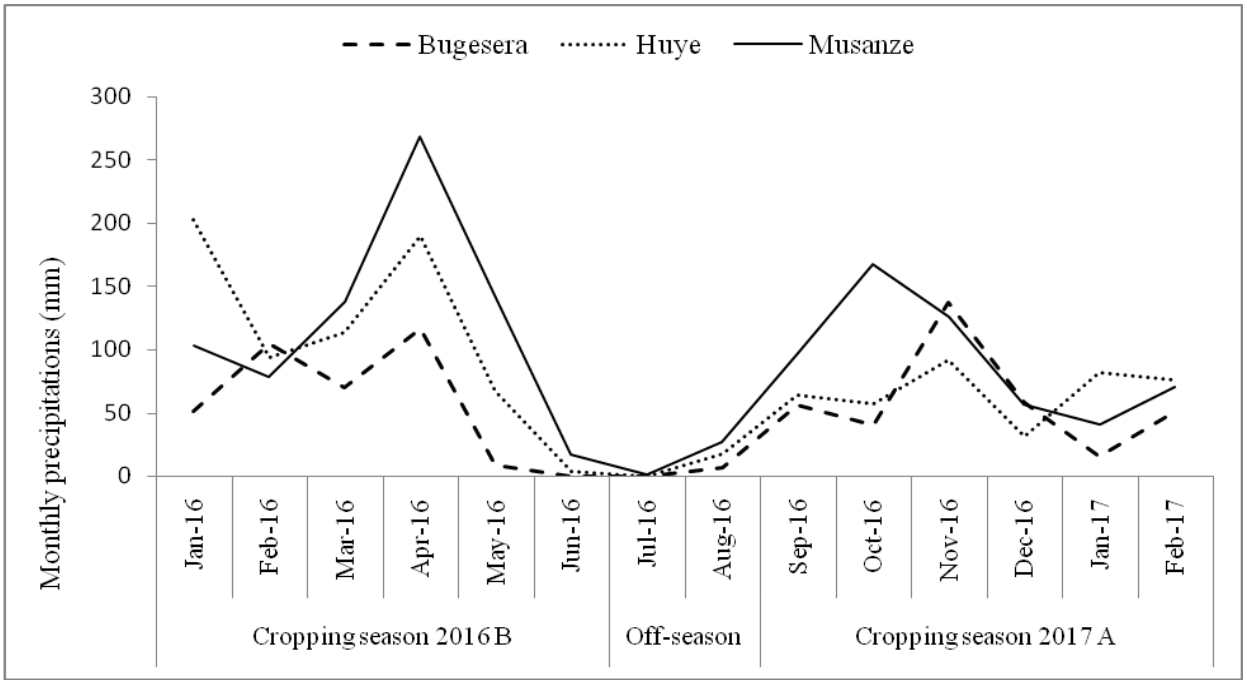


Figure 8: [4.2] Rainfall data on study sites during experimentation

The average minimum and maximum temperatures recorded were 15 and 28°C at Bugesera; 16 and 25°C at Rubona; 13 and 24°C at Musanze (Figure 9). A part from Musanze, these conditions fall in the range of weather requirements for bean crop of 16 to 24°C for temperature and an annual total rainfall of 600 to 650 mm (Beebe *et al*., 2013). However, as highlighted in Figure 8, the monthly rainfall distribution affected the performance of evaluated bean genotypes. For example in May 2016, the monthly mean rainfall was estimated at 9, 67 and 141 mm for Bugesera, Huye and Musanze, respectively. As this period coincided with pod setting (climbing) and seed filling (bush), the bean crop suffered from a terminal drought stress at Bugesera and Huye during may 2016 (2016B cropping season). In October 2016 (2017A copping season), the experiment suffered drought stress in early growth stages at Huye and was completely dry at Bugesera site. However, weather conditions were optimum for both seasons in highlands conditions (Musanze).

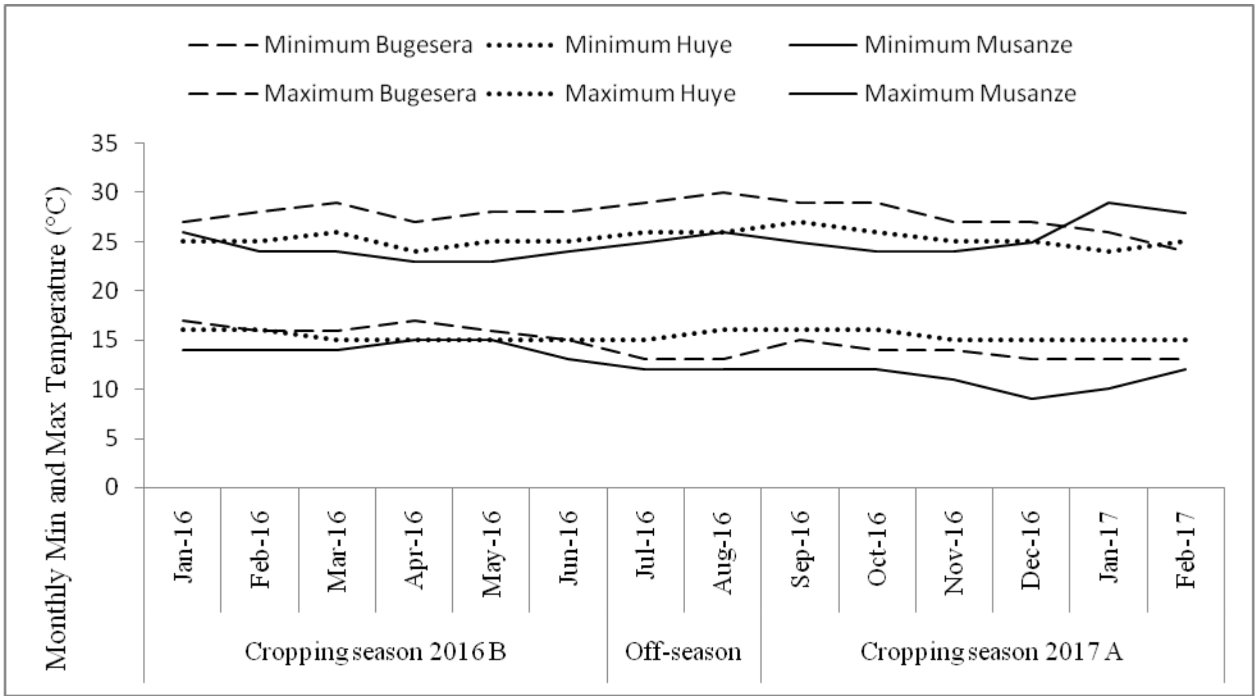


Figure 9: [4.3] Temperature data on study sites during experimentation

4.2.2. Treatments and experimental design

The experiment was laid out in a split-split-plot design with three different factors namely bean genotype with four levels (Akararakagenda, RWR2245, MAC44, RWV1129), plant growth stages with four levels (vegetative, flowering, pod setting and seed filling) and disease control measure with two levels (pesticide application and no pesticide application). Bean genotypes were randomly assigned to the whole plots, growth stages to sub-plots and disease control measure i.e. pesticide application to the sub-sub-plots. Experimental units consisted of seven rows that were 2 m long, with inter-row and intra-row spacing of 40 cm and 20 cm, respectively. For this study, Akararakagenda and RWR2245 bean genotypes were standing for bush bean type while MAC44 and RWV1129 were representing climbing bean type. Each bean genotype was planted in 8 plots giving a total of 32 plots for every participating farmer in all the three sites. A total of twenty four (24) farmers participated in this experiment i.e. 24 replicates as each participating farmer was considered as a replicate.

The treatments (bean genotypes and pesticide application regime) were evaluated at the on-set of the four plant growth stages i.e. vegetative, flowering, pod setting and seed filling (Table 11). These treatments were initiated at the fourth trifoliate leaf unfolded (V4) for vegetative stage, at one open flower (R1) for flowering, at early pod set (R3) for pod setting and at early seed fill (R5) for seed filling stage. For each plant growth stage, both Cypermethrin (insecticide) at a rate of 25 mg L^{-1} of water (spray volume of 1,000 - 2,000 L ha^{-1}) and Agro-Zeb 80WP (fungicide) at a rate of 2.5 g L^{-1} of water (spray volume of 500 - 1,000 L ha^{-1}) were applied as follows:

- For the “no pesticide application treatment”, the pesticide was not applied during vegetative, flowering, pod setting and seed filling plant growth stages.
- For the “pesticide application treatment”, the experimental plots were sprayed with pesticide before and at vegetative, flowering, pod setting and seed filling plant growth stages.

Plots were sown manually in rows and kept weed free during the growing cycle. Compound inorganic fertilizer (18-46-30) was applied at planting at a rate of unit ha^{-1} of N, P_2O_5 and K_2O_5. Woody stakes of 2.5 m height were used for staking climbing genotypes (MAC44, RWV1129).

Table 11: [4.1] Description of treatments

Growth stages	Treatments	Treatment description
Vegetative	P-V	Pesticide application at vegetative stage
	NP-V	No pesticide application from vegetative stage and throughout
Flowering	P-F	Pesticide application at vegetative and flowering
	NP-F	No pesticide application from flowering stage and throughout
Pod setting	P-P	Pesticide application at vegetative, flowering and pod setting
	NP-P	No pesticide application from pod setting stage and throughout
Seed filling	P-S	Pesticide application at vegetative, flowering, pod setting & seed filling
	NP-S	No pesticide application from seed filling stage and throughout

4.2.3. Yield and disease assessment

The experiment consisted of exposing the bean genotypes to natural bean disease pressure i.e. there was no artificial inoculation. Bean diseases developed naturally and relied on field inoculums and environmental conditions. While assessing the diseases symptoms exhibition, all observed diseases were recorded with a particular attention to the major bean diseases such as (i) fungal diseases (root rots, angular leaf spot, anthracnose, rust, ascochyta blight), (ii) bacterial diseases (common bacterial blight-CBB) and (iii) viral diseases (bean common mosaic virus-BCMV). Disease assessment was initiated from 10 to 15 days following each treatment application and continued every two weeks until crop maturity. Bean diseases were scored using the CIAT 1–9 (Table 12) developed visual scale (Schwartz, 1981; Van Schoonhoven & Pastor-Corrales, 1987).

Table 12: [4.2] Scale for bean disease and estimation of disease severity

Rating	Description	Severity (%)	Interpretation
1	Plants with no visible disease symptoms	0	Immune
3	Plants with light symptoms and few small lesions	1-2	Light infection
5	Plants with visible symptoms and several small lesions	3-10	Moderate infection
7	Plants with abundant and large lesions associated with chlorosis and necrosis	11-25	Heavy infection
9	Plants with large and coalescent lesions often associated with chlorosis resulting in severe and premature defoliation or plant death	> 25	Severe infection

Schwartz, 1981; Van Schoonhoven & Pastor-Corrales, 1987

Diseases and yield data were obtained from the five middle rows within a plot, disregarding 0.4 m at each row end to minimize border effects. Relative yield loss (L) from each plot was calculated as:

$$L\ (\%) = 100 \times \left[\frac{Y_{TP} - Y_{NP}}{Y_{TP}} \right]$$

Where, L is the percentage of grain yield loss, Y_{TP} is the yield measured on treated plot (healthy plants) and Y_{NP} the yield measured on non-treated plots (diseased plants).

As the yield data and bean disease severity are of different ranges, grain yield were normalized before fitting the regression analysis in order to eliminate the influence of each variable to another and then give features equal chances. The Min-Max Normalization was then used to normalize grain yield data.

$$Y_{Norm.} = \frac{Y_{Obs.} - \text{Minimum}}{\text{Maximum} - \text{Minimum}}$$

Where, $Y_{Norm.}$ is the normalized yield, $Y_{Obs.}$ is the observed grain yield

4.2.4. Statistical analysis

Bean disease scores/severities and yield data from each treatment were used for data analysis. Data on bean grain yield and disease severities at different bean growth stages were subjected to analysis of variance using GenStat 14th Edition (VSN International, 2011) to determine treatment effects. Mean differences among treatments were determined according to the Turkey's Honest Significant Difference Method. Correlation (r) analysis was carried out using Spearman's rank correlation of GenStat to determine the relationship between grain yield and bean disease severity at different growth stages. Furthermore, a linear regression model to predict yield loss was fitted as a function of severity at different growth stages. The significance of the model, the intercept (constant) and regression coefficient (slope/estimate) were tested using F-statistic.

4.3. Results

4.3.1. Disease severity

Simultaneous infection of common bean by a combination of several diseases; Angular Leaf Spot (ALS), Bean Common Mosaic Virus (BCMV), Ascochyta blight (ASCO) and Common Bacterial Blight (CBB), was observed. Among the three experimental sites, Bugesera had light disease severity (<2%) with moderate severity (3-7%) in Huye and Musanze sites. Angular leaf spot (ALS) and Bean Common Mosaic Virus (BCMV) were observed in the three bean-growing areas. However, ALS disease was more severe than BCMV (Table 13) particularly in Huye and Musanze. Both ALS and BCMV disease severities were significantly different among treatments with the highest severity scores observed for non-treated plants at vegetative stage for ALS and flowering stage for BCMV. Common bacterial blight (CBB) was also observed in Bugesera with high disease severity of 0.6% for non-treated plants at pod setting and seed filling. Ascochyta blight was also observed in Musanze with the highest disease severity of 6.6% for non-treated plots at pod setting stage. The maximum disease severities for ALS, CBB, BCMV and ASCO were, respectively, 6.8% (Rubona, NP-V), 0.6% (Bugesera, NP-P), 2.8% (Musanze, NP-P) and 6.6% (Musanze, NP-P). The treatment effects on bean disease severities were also investigated by comparing severities between the plots that received the pesticide treatment and the plots that did not receive the treatment. In all plots, natural infections of pathogens occurred; treated plots differed significantly from the non-treated plots in disease severity. As expected, the plots that did not receive the treatment had higher bean disease severities than the corresponding treated plots.

Table 13: [4.3] Disease severity (%) on bean varieties with or without pesticide at different growth stages

Treatments	Bugesera			Rubona			Musanze			Overall
	ALS	CBB	BCMV	ALS	BCMV	ASCO	ALS	ASCO	BCMV	
P-V	0.8	0.3	0.2^{b}	4.7^{b}	1.1^{b}	0.6^{ab}	3.4^{b}	4.8^{abc}	0.9^{c}	2.5^{ab}
NP-V	1.4	0.4	1.4^{a}	6.8^{a}	1.6^{ab}	1.1^{a}	5.5^{a}	6.5^{ab}	1.5^{abc}	4.1^{a}
P-F	0.9	0.0	0.3^{ab}	4.2^{b}	1.3^{ab}	0.5^{ab}	3.2^{b}	4.2^{c}	1.8^{abc}	1.1^{b}
NP-F	0.9	0.4	0.3^{ab}	3.7^{bc}	2.4^{a}	0.9^{ab}	3.8^{b}	5.4^{abc}	2.4^{ab}	1.9^{b}
P-P	1.0	0.2	0.0^{b}	3.7^{bc}	1.8^{ab}	0.2^{b}	2.5^{b}	4.2^{c}	1.2^{bc}	1.0^{b}
NP-P	1.5	0.6	0.0^{b}	3.5^{bc}	2.2^{a}	0.3^{ab}	3.3^{b}	6.6^{a}	2.8^{a}	2.0^{b}
P-S	0.5	0.2	0.0^{b}	2.4^{c}	1.4^{ab}	0.2^{b}	2.9^{b}	4.7^{bc}	1.4^{abc}	1.1^{b}
NP-S	1.6	0.6	0.5^{ab}	2.3^{c}	1.9^{ab}	0.2^{ab}	3.5^{b}	5.9^{abc}	1.6^{abc}	2.3^{ab}
P-value	0.070	0.212	0.005	<0.001	0.027	0.004	<0.001	<0.001	0.003	<0.001

V =Vegetative, F =Flowering, P =Pod setting, S =Seed filling, P- =Pesticide application, NP- =No pesticide application; ALS=Angular leaf spot, BCMV=Bean Common Mosaic Virus, CBB=Common Bacterial Blight, ASCO=Ascochyta blight; Values in the same column with different letters differ significantly ($p \leq 0.05$) according to ANOVA and Turkey's Honest Significant Difference method; Disease severity evaluation: 0% = no infection; 1-2% = light infection; 3-10% = moderate infection; 11-25% = heavy infection and >26% = severe infection.

4.3.2. Grain yield

For bush bean genotypes, grain yields ranged between 1,101 kg ha^{-1} (Rubona, NP-P) and 2,540 kg ha^{-1} (Bugesera, P-S). For climbing bean genotypes the yield ranged between 1,084 kg ha^{-1} (Bugesera, NP-P) and 2,881 kg ha^{-1} (Musanze, P-S). For each plant growth stage, bean grain yields were significantly ($P<0.001$) higher for sprayed plots with pesticide than non-sprayed plots for both bush and climbing beans (Table 14).

Table 14: [4.4] Effect of pesticides at different growth stages on bean grain yield

Treatments	Bugesera (kg/ha)		Huye (kg/ha)		Musanze (kg/ha)		Overall (kg/ha)	
	Bush	Climbing	Bush	Climbing	Bush	Climbing	Bush	Climbing
P-V	$2,298^{ab}$	$1,732^{a}$	$1,539^{ab}$	$1,501^{a}$	$1,967^{abc}$	$2,774^{ab}$	$1,839^{a}$	$2,039^{a}$
NP-V	$2,126^{ab}$	$1,314^{ab}$	$1,292^{bc}$	$1,218^{ab}$	$1,632^{bcd}$	$2,377^{bc}$	$1,570^{b}$	$1,688^{b}$
P-F	$2,177^{ab}$	$1,474^{ab}$	$1,639^{a}$	$1,564^{a}$	$2,017^{ab}$	$2,849^{a}$	$1,881^{a}$	$2,051^{a}$
NP-F	$1,813^{ab}$	$1,152^{b}$	$1,321^{bc}$	$1,223^{b}$	$1,601^{cd}$	$2,359^{bc}$	$1,516^{bc}$	$1,655^{b}$
P-P	$2,012^{ab}$	$1,290^{ab}$	$1,401^{ab}$	$1,548^{a}$	$1,898^{abc}$	$2,723^{ab}$	$1,702^{ab}$	$1,963^{a}$
NP-P	$1,716^{b}$	$1,084^{b}$	$1,101^{c}$	$1,206^{b}$	$1,439^{d}$	$2,083^{c}$	$1,340^{c}$	$1,528^{b}$
P-S	$2,540^{a}$	$1,562^{ab}$	$1,491^{ab}$	$1,677^{a}$	$2,134^{a}$	$2,881^{a}$	$1,925^{a}$	$2,128^{a}$
NP-S	$1,991^{ab}$	$1,369^{ab}$	$1,266^{bc}$	$1,138^{b}$	$1,712^{bcd}$	$2,493^{abc}$	$1,567^{bc}$	$1,708^{b}$
P-value	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

V =Vegetative, F =Flowering, P =Pod setting, S =Seed filling, P- =Pesticide application, NP- =No pesticide application; Within the same column, values that differ according to analysis of variance ($p \leq 0.05$) and Turkey's Honest Significant Difference Method are marked with different small letters

The highest grain yields were observed for sprayed plots at all the four plant developmental stages i.e. pesticide application at vegetative, flowering, pod setting and seed filling stages (P-S). The lowest marketable bean yield was recorded for the no pesticide application from pod setting stage and throughout (NP-P). Yield losses due to observed natural bean disease pressure were higher (21%) for no pesticide application from pod setting stage and throughout (Table 15).

Table 15: [4.5] Estimated bean yield loss without pesticide application at different growth stages

Growth stage	Bugesera			Huye			Musanze			Overall loss (%)
	Treated	Non-treated	Loss (%)	Treated	Non-treated	Loss (%)	Treated	Non-treated	Loss (%)	
Vegetative	2,015	1,720	16	1,520	1,255	18	2,371	2,005	16	17
Flowering	1,826	1,483	20	1,602	1,272	21	2,433	1,980	19	20
Pod setting	1,651	1,400	16	1,475	1,154	22	2,311	1,761	24	21
Seed filling	2,051	1,680	17	1,584	1,202	24	2,508	2,103	17	19

4.3.3. Relation of grain yield to observed bean diseases

The correlation coefficient (r) for the relation between grain yield and severities of observed diseases (ALS, ASCO, CBB and BCMV) showed inverse relationship (Table 16). Meaning that bean yield was inversely ($P<0.001$) correlated to ALS, BCMV and ASCO severities as also depicted by the negative slope of the trend lines in Figure 10. The high negative correlation between grain yield and observed bean diseases severities were observed at flowering (r = -0.266), pod setting (r = -0.312) and at seed filling (r = -0.318).

Table 16: [4.6] Correlation coefficient (r) values between grain yield and observed disease severities

Growth stage	ALS		ASCO		CBB		BCMV	
	Corr. r	P-value	Corr. r	P-value	Corr. r	P-value	Corr. R	P-value
Vegetative	-0.306	<0.001	-0.265	<0.001	-0.134	0.070	-0.264	<0.001
Flowering	-0.156	0.034	-0.266	<0.001	-0.042	0.575	-0.259	<0.001
Pod setting	-0.169	0.022	-0.207	0.005	-0.142	0.054	-0.312	<0.001
Seed filling	-0.318	<0.001	-0.230	0.002	-0.011	0.886	-0.222	0.002
Overall	-0.306	<0.001	-0.265	<0.001	-0.134	<0.070	-0.264	<0.001

ALS=Angular leaf spot, BCMV=Bean Common Mosaic Virus, CBB=Common bacterial blight, ASCO=Ascochyta; Disease severity scale: 1 = no infection, 5 = severe infection

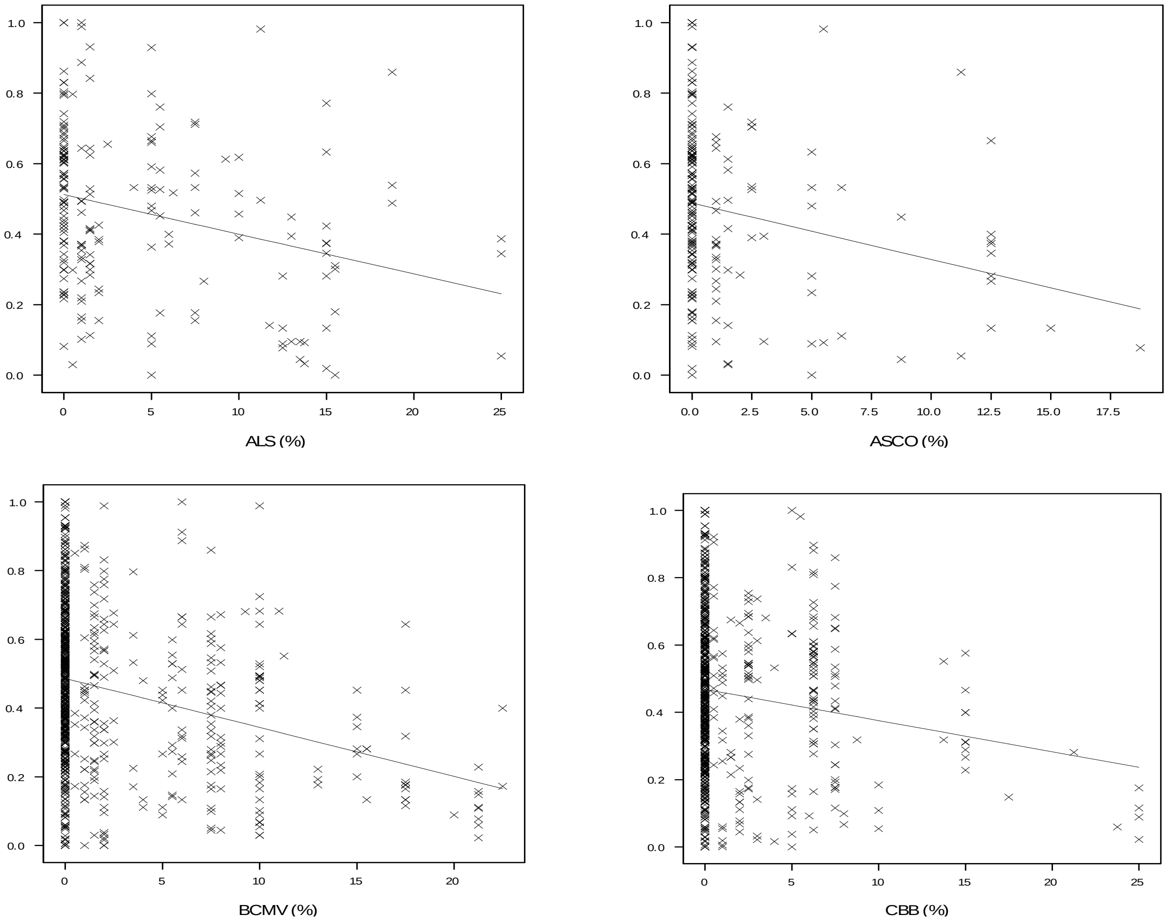


Figure 10: [4.4] Relationship between grain yield and severity of observed diseases

A linear regression model relating grain yield to bean diseases severities was developed to predict yield losses (Table 17). For this model, we used data from the three bean diseases (ALS, ASCO and BCMV) for which severities were significantly (P<0.001) inversely correlated to grain yield. The estimated regression coefficients are (-0.009) for ALS, (-0.011) for BCMV and (-0.002) for ASCO. Based on these estimates, the relationship between grain yield and severity of observed diseases can be written in the following equation:

Grain yield = 0.5107 – 0.009*ALS – 0.011*BCMV

These estimates predict that for every percentage increase in ALS and BCMV severities decreases bean yield by 0.9% and 1.1%, respectively.

Table 17: [4.7.] Relationship between grain yield and severities of observed bean diseases

Parameter	Vegetative		Flowering		Pod setting		Seed filling		Overall	
	Estimate	P-value	Estimate	P-value	Estimate	P-value	Estimate	P-value	Estimate	P-value
Constant	0.5290	<0.001	0.5182	<0.001	0.4650	<0.001	0.5394	<0.001	0.5107	<0.001
ALS	-0.009	0.004	-0.008	0.052	-0.008	0.101	-0.017	<0.001	-0.009	<0.001
ASCO	-0.002	0.968	-0.005	0.623	-0.008	0.289	-0.001	0.902	-0.002	0.541
BCMV	-0.011	0.021	-0.014	0.002	-0.007	0.068	-0.008	0.093	-0.011	<0.001

ALS = Angular leaf spot, BCMV = Bean Common Mosaic Virus, CBB = Common bacterial blight, ASCO = Aschochyta

4.4. Discussion

4.4.1. Disease severity

Angular leaf spot (ALS), Bean common mosaic virus (BCMV), and Ascochyta leaf spot (ASCO) were the most significant bean diseases observed in the farmers' field experiments. The occurrence of these diseases in the study sites could be attributed to the prevailing weather conditions during the experimentation period being favourable for pathogens development. According to Mwang'ombe *et al.* (2007) and Pamela *et al.* (2014), bean disease severities are significantly influenced by agro-ecology, altitude and humidity with ALS, ASCO and BCMV being favored by cool-moderate temperatures of 16 to 28^{o}C, 16 to 24^{o}C and 20 to 25^{o}C, respectively. These results are also in accordance with those of Aggarwal *et al*. (2004); Pamela *et al*. (2014); De Jesus Junior *et al.* (2003); Bassanezi *et al.* (2001); Olango *et al.* (2016); Lemessa *et al*. (2011) and Mavric & Sustar-Vozlic (2004), who reported ALS, ASCO and BCMV diseases among the most important biotic constraints of *Phaseolus vulgaris* in both tropical and subtropical areas.

Throughout the experiment, disease severity levels were generally low with most treatments having plants with no symptoms, light or visible small lesions with limited sporulation. The low disease severity levels are attributed to the use of disease tolerant bean genotypes and low field inoculums as the trials were installed in fields not previously planted to beans. A part from the local bean variety, the rest of evaluated bean genotypes were recently (2013-2016) released in Rwanda, Burundi and Kenya based on their nutrition profile, high yield potential, and bean disease tolerance (Larochelle & Alwang, 2014).

4.4.2. Grain yield loss

The present study indicated that, the maximum relative yield losses of 20% and 21% were obtained in the non-treated plots at flowering and pod setting stage, respectively. The high percentage of yield loss at flowering is attributed to the leaf lesions which lead to premature defoliation and reduced amount of light energy intercepted by the plant canopy. Whereas pod lesions during pod development stage resulting in seed rotting may account for the high percentage of yield loss at seed filling stage. These results are in accordance with Ploper *et al.* (2002) in Lemessa *et al.* (2011) who reported an average yield loss of 32.35% for a single fungicide application at flowering (35 days after sowing) and 22.45% for double fungicide applications at flowering and pod development stages (50 days after sowing).

While studying the effect of ALS on bean yield loss, De Jesus Junior *et al*. (2001) and Lemessa *et al*. (2011) found defoliation to be the major factor that leads to a reduction of the total leaf area helpful for photosynthesis. Whereas, Lopes & Berger (2000) reported a reduced capacity of diseased leaves in performing photosynthesis, likely to reduce the efficiency with which the intercepted radiation is utilized by the plant. Goodwin (1992), Osdaghi *et al*. (2009) and Lemessa *et al*. (2011) also reported that high level of bean disease at pod filling stage may have a major influence on yield loss since much of the bean yield accumulates during this plant growth stage.

In the absence of adequate disease control measure, Mersha & Hau, (2011) reported that earliness of leaf and pod infection can highly reduce the grain yield of common bean (yield loss greater than 50%). He recommended at least two fungicide application against ALS in Canada one at pre-flowering stage and another one at pod development stages.

4.4.3. Relation of grain yield to observed bean diseases

The study demonstrated inverse and linear relationships between grain yield and ALS, BCMV, and ASCO severities. Diseased plants are characterized by physiological disturbances caused by disease pathogens. These plant malfunctions limit both plant growth and development. The higher the plant is exposed to the physiological disturbances the higher the yield decreases. Bergamin-Filho *et al*. (1997), De Jesus Junior et al. (2001), De Jesus Junior *et al.* (2003) and Mersha & Hau (2011) also reported an inverse and linear relationship between bean disease and yield. Similar findings have been reported for diseases of beans and several crop plants. For example Anthracnose disease of common beans (Nkalubo *et al.*, 2007), Sclerotinia stem rot of Canola (Del Rio *et al.*, 2007) and Northern leaf blight of sweet corn (Pataky *et al*, 1998).

Although all the observed diseases reduced the bean yield, ALS and BCMV had higher contribution to the yield decrease. The regression estimates that for every 1% increase in ALS and BCMV severity, there was a grain yield loss estimated at 0.9% and 1.1%, respectively. This is attributed to the negative effect that these diseases have on both leaves and pods. These results are in agreement with findings from Worthman (1992) where the yield losses were estimated at 9.1 kg/ha and 3.9 kg/ha for a 1% increase in severity of anthracnose and ALS, respectively. Similarly, Stenglein *et al.* (2003) in Pamela *et al.* (2014) reported that every 10% increase in ALS severity results in 7.9% yield loss of common bean.

4.5. Conclusion

Under natural bean disease pressure ALS, BCMV, ASCO and CBB were observed in all the three bean growing areas of Rwanda, although diseases severities were higher in mid and high altitude comparing to low land conditions. Among these observed bean disease ALS was recorded throughout the study regions with highest disease severity, followed by BCMV and Ascochyta blight. As evidenced in the study, grain yield was negatively correlated to bean disease severity. The highest bean losses were observed when pesticide was not applied at flowering and pod setting stages. This calls for the use of pesticide at flowering and pod setting stages in order to curb yield losses and optimize bean production in Rwanda, particularly in mid and highland conditions. However, cost benefit analysis of pesticide use to manage pest and disease for dry bean production in high, medium and low land conditions of Rwanda needs to be determined.

CHAPTER FIVE

CALIBRATING DSSAT MODEL TO ESTIMATE AREA YIELD INDEX INSURANCE PREMIUM FOR COMMON BEAN AT DIFFERENT GROWTH STAGES AND WEATHER PERILS

Abstract

This study investigated the potential of using a crop simulation model to predict bean yield losses and estimate subsequent payable insurance premium rates for weather perils (drought, waterlogging and natural bean disease pressure) occurring at different plant developmental stages. CROPGRO-Dry bean module of DSSAT model was calibrated and validated using observed yield data collected from field experiments conducted in three bean growing areas of Rwanda (Bugesera, Huye and Musanze). These experiments were conducted to determine the most sensitive stages of bean growth to natural bean disease pressure, drought stress and waterlogging and their impact on yield losses. The calibrated model showed good agreement between predicted and observed bean yields with relative root mean square error (RRMSE) of around 0.5 for both drought and waterlogging and around 1.5 for natural bean disease pressure. The estimated yield losses due to investigated treatments were further used to estimate corresponding insurance premium rate of an area yield index insurance model. Drought effects were severe at seed filling stage with bean yield reduction rate estimated at 23% and a corresponding premium rate of 257 kg ha^{-1}. Pod setting stage was the most sensitive to natural bean disease pressure with yield reduction rate of 30% and a corresponding premium rate of 467 kg ha^{-1}. Seed filling was most sensitive to waterlogging with yield reduction of 28% and a corresponding premium rate of 429 kg ha^{-1}. This research provides useful information to insurance providers to focus most on pod developmental stages when setting up area yield index insurance products to protect bean farmers against drought, waterlogging and natural bean disease pressure.

Keywords: area yield index insurance, CROPGRO, *Phaseolus vulgaris,* premiums, Rwanda.

5.1. Introduction

The unaffordable premium rates associated with too slow process of making payouts for the traditional indemnity based agricultural insurance have led to the development of index-based insurance products (Daron & Stainforth, 2014). Despite its associated basis risk, where insured may experience a loss but receive no payout or experience no loss but receive payout, index-based insurance is a promising insurance option, especially for developing economies where transactions costs tend to be high. Due to its low administration costs, index-based insurance provides an attractive alternative for small-holder farmers and insurers in developing countries (Barrett *et al.*, 2007; Daron & Stainforth, 2014; Leblois *et al.*, 2014).

While targeting to insure small-scale farmers, Syngenta Foundation for Sustainable Agriculture (SFSA) developed index-based insurance products (Area Yield Index Insurance and Weather Index Insurance). The SFSA found these products best appropriate to address the vulnerability of farmers to weather related perils. The costs associated to the implementation of these insurance products are relatively affordable (thus relatively sustainable) by small-scale farmers since their premiums are low with low/moderate transaction costs (World Bank, 2015). In East Africa region, these products are being implemented by Agriculture and Climate Risk Enterprise Ltd (ACRE-Africa). In partnerships with local insurance companies, ACRE-Africa is demonstrating positive development impact with index based crop insurance in Kenya, Rwanda and Tanzania (World Bank, 2015; Ntukamazina *et al.*, 2017). The enterprise has shown rapid scale-up in the region, cumulatively, by the end of 2016 over 1,000,000 farmers were insured in the three countries, and is projected to reach 3,000,000 farmers across ten Africa countries by 2018 (ACRE-Africa, 2017). Despite this positive achievement, resource limited farmers are reluctant to buy the area yield index insurance product as it is being sold as full season cover compared to the three phase maize insurance contract (Nganga, 2013; Ntukamazina *et al.*, 2017).

Therefore, the objective of this study was therefore to determine actuarially fair premiums for an area yield index insurance product for common bean based on the effect of drought, waterlogging and natural bean disease pressure at different plant growth stages. The study investigated to what extent, drought, waterlogging and natural bean disease pressure observed at a particular plant growth stage, can be utilized to explain bean yield losses and subsequently estimate guaranteed yield and payouts for an area yield index insurance product.

5.2. Materials and Methods

5.2.1. Selection of the study area

According to Barrett *et al.* (2007) area yield insurance contracts must be based on an index of area yields. In order to reduce basis risk, the area or zone boundaries for an area yield contract should be selected so as to group together the largest number of farms with similar soils and climate conditions. Based on elevation, rainfall pattern and soils conditions, Baligira (2008) distinguished three main agro-climatic zones in Rwanda: (i) High land region, (ii) Eastern and central plateau, and (iii) Western low land. These agro-climatic zones have significant inter-variation of climatic conditions but with less intra-variation within each agro-climatic zone. In Rwanda, districts are considered as administrative entities for which sufficient yield data are available as the seasonal agriculture surveys report data on a district basis. Therefore, three districts were selected for this study namely Bugesera for the low land zone, Huye for the plateau zone and Musanze for the high land region.

5.2.2. Experimental data

Greenhouse and on-farm experiments were conducted to estimate bean yield losses due to water stress and natural bean disease pressure at different plant growth stages. On one hand, under netted greenhouse, an experiment was conducted for two growing periods (September 2015-February 2016 and March-July 2016) to determine the most sensitive stages of bean growth to water-stressed conditions and their impact on grain yield. The effect of watering regime treatment with three levels (drought stress, waterlogging and control) on yield of dry beans was investigated. Two bean genotypes [RWR2245 (bush) and MAC44 (climbing)] were used for this experiment. Drought and waterlogging stress treatments were imposed at vegetative, flowering, pod setting and seed filling stages. On the other hand, on-farm experiment was conducted in Musanze, Huye and Bugesera districts for two successive cropping seasons (March-July 2016 and September-February 2017), to quantify the amount of yield loss due to natural bean disease pressure and investigate the relationships between disease and yield of common bean. The evaluated treatments consisted in applying or not applying pesticide (insecticide and fungicide) at the on-set of the four plant growth stages i.e. vegetative, flowering, pod setting and seed filling stage. Four bean genotypes with different growth habit [bush type (Akararakagenda, RWR2245), climbing type (MAC44 and RWV1129)] were used for the on-farm experiment. However, results reported in this chapter are limited to those for MAC44 and RWR2245 for purposes of harmonizing data with that from greenhouse experiment.

5.2.3. Calibrating DSSAT model to estimate bean yield losses

Description of DSSAT Crop Simulation Model

Decision Support System for Agro-technology Transfer (DSSAT) is an integrated computer system developed to analyze, separately, the effects of the changes of soil characteristics or weather pattern on crop development, which is difficult to achieve in field experiments (Rezzoug *et al*., 2008). DSSAT model is composed of various crop simulation models which include the CERES model for cereals (barley, maize, sorghum, millet, rice and wheat); the CROPGRO model for legumes (dry bean, soybean, peanut and chickpea); and SUBSTOR model for root crops (cassava, potato) and CROPSIM model for other crops such as sugarcane, tomato, sunflower and pasture (Chunlei *et al*., 2013; Khan & Walker, 2015).

Model data requirements

The minimum data set requirements (Table 18) for running the DSSAT models include data on (i) experimental site, (ii) daily weather during the growing cycle; (iii) soil characteristics, (iv) initial conditions at the start of the growing cycle, and (v) crop management (Jones *et al.*, 2003).

Table 18: [5.1] Minimum data set requirements for operation of the DSSAT models

Site	– Latitude and longitude, elevation; average annual temperature; average annual amplitude in temperature – Slope and aspect; major obstruction to the sun (e.g. nearby mountain); drainage (type, spacing and depth); surface stones (coverage and size)
Weather	– Daily solar radiation, maximum and minimum air temperatures, precipitation
Soil	– Classification using the local system and the USDA-NRCS taxonomic system – Basic profile characteristics by soil layer: in situ water release curve characteristics (saturated drained upper limit, lower limit); bulk density, organic carbon; pH; root growth factor; drainage coefficient
Initial conditions	– Previous crop, root, and nodule amounts; numbers and effectiveness of rhizobia – Water, ammonium and nitrate by soil layer
Management	– Cultivar name and type – Planting date, depth and method; row spacing and direction; plant population – Irrigation and water management, dates, methods and amounts or depths – Fertilizer (inorganic) and inoculants applications – Residue (organic fertilizer) applications (material, depth of incorporation, amount) – Tillage (where appropriate), Environment (aerial) adjustments – Harvest schedule

Source: Jones *et al.*, 2003

For this study, the set of weather input data were taken from 1971 through 2016 and included solar radiation, monthly precipitation, and maximum and minimum air temperatures. These data were provided by the Rwanda Meteorology Agency. Data on the top-soils of experimental sites (Bugesera, Huye and Musanze) were provided by the Rwanda Agriculture Board (RAB) in addition to the relevant information reported in Verdoodt & Rast (2006), Mbonigaba *et al.* *(*2009), Rushemuka *et al.* (2014) and Hengl *et al.* (2017).

Model calibration and validation

Data collected from two field experiments conducted during 2016-2017 cropping seasons were used to calibrate and validate CROPGRO-Dry bean model of DSSAT. Specifically, for the model calibration, genetic coefficients (Table 19) were adjusted by using observed data on phenology, morphology, growth and harvest from the first field experiment conducted during the period of February to July 2016. Whereas, data collected from the second field experiment conducted during the period of September 2016 to February 2017 were used for the model validation. Relative Root Mean Square Error (RRMSE) was used as a statistical test to calculate the deviation between predicted and measured values (Wu *et al.*, 2013; Singh *et al*., 2013).

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - P_i)^2}}{X_{av}}$$

Where, N is the number of observations; X_i are the measured values; X_{av} is the average of the measured X_i values and P_i being the simulated (predicted) values.

The relative yield loss due to the effect of each treatment on grain yield of both bush and climbing bean was estimated in percentage of yield decrease (%).

$$Y_D = 100\ x \left[\frac{Y_C - Y_T}{Y_C}\right]$$

Where: Y_D is the percentage of grain yield decrease; Y_C is the average yield obtained under the control “C”; and Y_T is the average yield obtained under the treatment “T”

Table 19: [5.2] Genetic coefficients used in simulation

Coefficients	Units	Range		Cultivars		FLAG
		Minimum	Maximum	RWR2245	MAC44	
CSDL	Hour	12.17	12.17	12.17	12.17	0
PPSEN	1/hour	0.070	0.070	0.050	0.000	0
EM.FL	photo-thermal days	20.00	35.00	31.00	29.00	1
FL.SH	photo-thermal days	2.000	2.000	2.000	2.000	0
FL.SD	photo-thermal days	6.000	13.00	8.000	10.00	1
SD.PM	photo-thermal days	14.00	29.00	15.00	20.00	1
FL.LF	photo-thermal days	6.000	6.000	6.000	6.000	0
LFMAX	mg CO2/m2-s	1.000	1.000	1.000	1.000	0
SLAVR	cm^2 g^{-1}	250.0	350.0	320.0	320.0	2
SIZLF	cm^2	133.0	180.0	133.0	133.0	2
XFRT		1.000	1.000	1.000	1.000	0
WTPSD	G	0.220	0.660	0.460	0.400	2
SFDUR	photo-thermal days	11.00	22.00	12.00	15.00	2
SDPDV	Number pod^{-1}	3.000	5.000	3.500	5.500	2
PODUR	photo-thermal days	4.000	16.00	10.00	10.00	2
THRSH	Threshing percentage	78.00	78.00	78.00	78.00	0
SDPRO	g(protein) g(seed)$^{-1}$	0.235	0.235	0.240	0.240	0
SDLIP	g(oil) g(seed)$^{-1}$	0.030	0.030	0.030	0.030	0

CSDL: Critical Short Day Length below which reproductive development progresses with no day length effect (for short day plants) (hour); PPSEN: Slope of the relative response of development to photoperiod with time (positive for short day plants); EM.FL: Time between plant emergence and flower appearance (R1); FL.SH: Time between first flower and first pod (R3); FL.SD: Time between first flower and first seed (R5); SD.PM: Time between first seed (R5) and physiological maturity (R7); FL.LF: Time between first flower (R1) and end of leaf expansion (photo-thermal days); LFMAX: Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light; SLAVR: Specific leaf area of cultivar under standard growth conditions; SIZLF: Maximum size of full leaf (three leaflets); XFRT: Maximum fraction of daily growth that is partitioned to seed + shell; WTPSD: Maximum weight per seed; SFDUR: Seed filling duration for pod cohort at standard growth conditions; SDPDV: Average seed per pod under standard growing conditions; PODUR: Time required for cultivar to reach final pod load under optimal conditions; THRSH: The maximum ratio of (seed/(seed+shell)) at maturity; SDPRO: Fraction protein in seeds; SDLIP: Fraction oil in seeds. The FLAG column indicates which coefficients are to be estimated using either phenology measurements (FLAG=1), using growth measurements (FLAG=2) or which coefficients are not to be estimated (FLAG=0).

Source: Adapted from Hoogenboom *et al.* (2010)

Simulation scenarios were defined to ensure the treatment was overlying phenological stages. An illustrative example is provided in Figure 11 showing water stress index (drought) for MAC44 at vegetative, flowering, pod setting and seed filling growth stages. The red line (y=0, x axis), indicating no water stress for recommended irrigation, the yellow, green, black and blue curves indicating a 0.8 water stress (y=0.8) at vegetative, flowering, pod setting and seed filling, respectively.

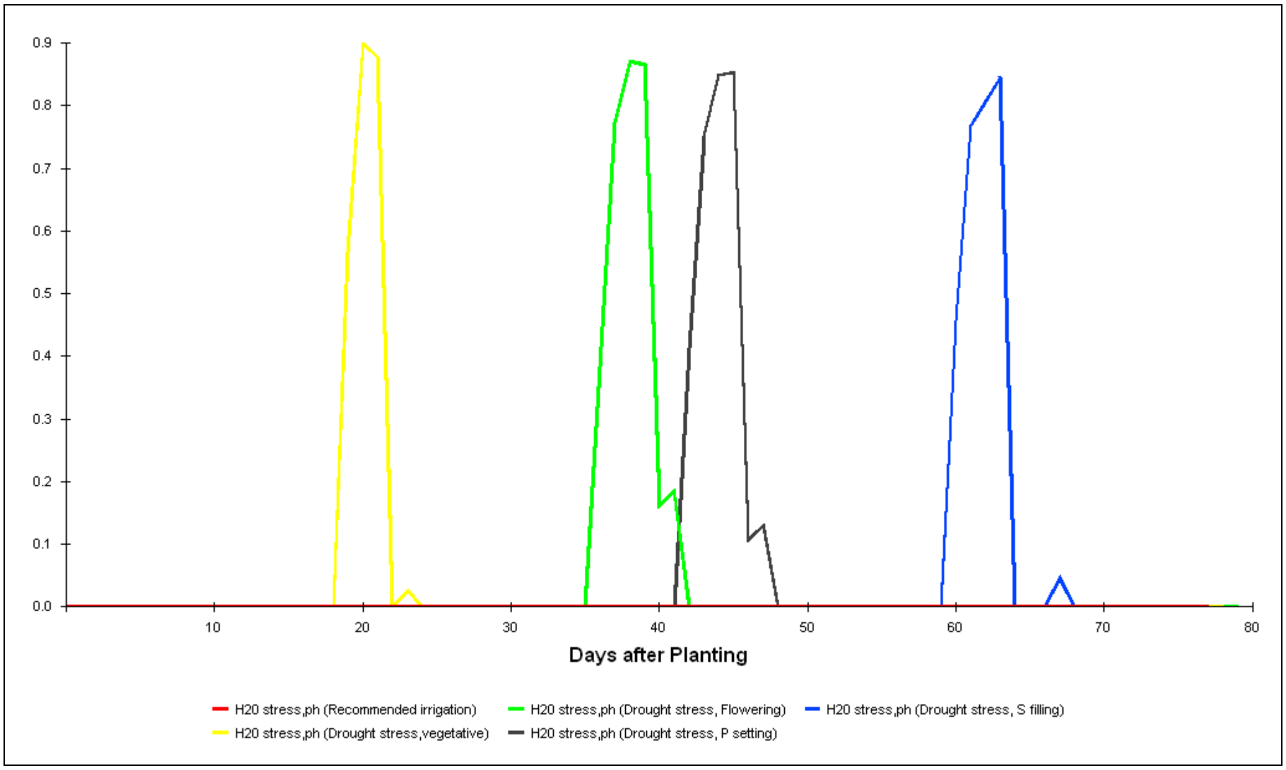


Figure 11: [5.1] Overview of stress index for water stress at different growth stages of MAC44

5.2.4. Calculation of area yield index insurance premium rate

Determination of insurance premium rates started with the calculation of expected loss. In the case of yield insurance, historical yield experience is used to calculate the expected loss (Skees *et al.*, 1997). The calculation of area premium rates used by this paper follows the procedures in Skees *et al.*, (1997) and Miranda (1991) as presented below:

For any given crop year, the area yield, y, is a random variable. The insurer's forecast of the area yield is given by $yfcast$. The insured selects a $scale$ of between 0.9 and 1.5, and a yield coverage level (cov) of between 0.7 and 0.95. Binici & Zulauf (2006) denoted the yield coverage level as a smoothing constant (α) that lies between 0 and 1.

The critical or guaranteed yield is calculated as:

$$(1) \qquad y_c = yfcast \; x \; \mathrm{cov}.$$

The insured receives an indemnity, $indem$, whenever $y < y_c$. The indemnity is calculated as

$$(2) \qquad Indem = \max \left[\left(\frac{y_c - y}{y_c} \right) (yfcast)(scale), \; 0 \right]$$

Where Indem represents the indemnity unit of production per insured unit or, dollar value per insured unit, representing the pay-out policyholders receive when they experience losses. In the extreme case of zero actual yields, the percentage shortfall is 100% and the indemnity is equal to $(yfcast)(scale)$, which is the insurer's liability (the insurer's protection), or the maximum possible indemnity payment. According to Miranda (1991) and Skees *et al. (*1997), a farmer should be allowed to "over insure" the crop if the yield variability is greater for the farm than the area. In our study, coverage levels were set at 80%, 90%, 100% and 110%.

The simulated grain yields by CROPGRO-Dry bean model were used to calculate the expected bean yield losses due to the selected weather related stresses. For each treatment, the simulated grain yield was utilized to estimate area yield index insurance premium rate through the following major steps:

Step 1: The simulated grain yield for the control treatment was considered as the forecast area yield"$yfcast$" and simulated grain yield for other treatments considered as the actual area mean yield "y" for the corresponding treatments.

Step 2: With a yield coverage level of 0.85 (α=85%), equation (1) was used to calculate the Guaranteed or Trigger Area Yield " y_c "

Step 3: Given the indemnity payment rule stated in Equation (2), expected premium rates were computed for each treatment and for four indemnity scale levels of 80%, 90%, 100% and 110%.

5.3. Results

5.3.1. Model calibration and validation

The calibration of the CROPGRO-Dry bean model consisted of adjusting values of the non-conservative genetic coefficients using the observed data from first field experiment (Feb-July 2016). The model was validated using data collected from the second field experiment (September 2016 to January 2017). The two bean genotypes presented differences for the following parameters: time between plant emergence and appearance of the first flower (EM.FL), time between first flower and first pod (FL.SD), time between first seed and physiological maturity (SD.PM), maximum weight per seed (WTPSD), seed filling duration for pod cohort at standard growth conditions (SFDUR), and average seed per pod under standard growing conditions (SDPDV). Results presented in Table 20 illustrate the comparison between observed and predicted grain yield (kg ha^{-1}) of the two common bean genotypes under the specified growing conditions. The model performance was evaluated using the Relative Root Mean Squared Error (RRMSE) as a statistical tool for comparing observed and predicted values. Observed and predicted bean grain yield (kg ha^{-1}) for the investigated treatments in the study sites are presented in Appendix 3.

Table 20: [5.3] Observed and predicted grain yield (kg ha-1) for evaluated treatments

Treatments	RWR2245			MAC44		
	Observed	Simulated	RRMSE	Observed	Simulated	RRMSE
Control	3,105	2,729	0.281	4,013	4,278	0.395
DS-V= Drought stress at vegetative	2,576	2,424	0.208	3,235	3,874	0.406
DS-F= Drought stress at flowering	2,602	2,207	0.328	3,339	3,748	0.392
DS-P= Drought stress at pod setting	2,241	2,294	0.366	3,378	3,619	0.450
DS-S= Drought stress at seed filling	2,661	2,073	0.371	3,146	3,329	0.552
WL-V= Waterlogging at vegetative	1,846	2,192	0.412	2,493	3,014	0.769
WL-F= Waterlogging at flowering	2,714	2,179	0.347	2,165	3,133	1.010
WL-P= Waterlogging at pod setting	2,660	2,167	0.344	3,288	3,186	0.563
WL-S= Waterlogging at seed filling	2,601	1,973	0.355	2,923	3,088	0.555
NP-V= No pesticide use at vegetative	2,218	2,729	0.696	3,393	4,278	1.715
NP-F= No pesticide use at flowering	2141	2,729	0.830	3,327	4,278	1.678
NP-P= No pesticide use at pod setting	1,893	2,729	1.167	3,072	4,278	1.839
NP-S= No pesticide use at seed filling	2,213	2,729	0.805	3,434	4,278	1.555

RRMSE = Relative Root Mean Square Error

5.3.2. Estimation of bean yield losses due to drought, waterlogging and natural disease pressure

The results from the model validation were used to assess the extent to which evaluated treatments reduced bean grain yield (Table 21). In other words, simulated results were used to estimate in percentage of yield decrease (%), the effect of each treatment on grain yield of both bean genotypes (RWR2245 and MAC44). However, as the model failed to simulate grain yield variation due to pesticide application treatment, the rate of yield reduction for this treatment was estimated using observed data. Seed filling stage was the most sensitive to drought stress with an estimated yield reduction of 24% for RWR2245 and 22% for MAC44. Seed filling stage were the most sensitive to waterlogging conditions with an estimated yield reduction of 28% for both MAC44 and RWR2245.

For both bean genotypes, pod setting was the most sensitive stage to the natural bean disease pressure with an estimated yield reduction rate of 31% for RWR2245 and 28% for MAC44.

Table 21: [5.4] Effect of water stress and no pesticide use throughout growth stages on bean yield loss

Weather stress	Growth stage	Treatment	RWR2245		MAC44	
			Simulated	Loss (%)	Simulated	Loss (%)
	-	Control	2,729	0	4,278	0
Drought stress	Vegetative	DS-V	2,424	11	3,874	9
	Flowering	DS-F	2,207	19	3,748	12
	Pod setting	DS-P	2,294	16	3,619	15
	Seed filling	DS-S	2,073	24	3,329	22
Waterlogging	Vegetative	WL-V	2,192	20	3,014	30
	Flowering	WL-F	2,179	20	3,133	27
	Pod setting	WL-P	2,167	21	3,186	26
	Seed filling	WL-S	1,973	28	3,088	28
Natural bean disease pressure (no pesticide application)	Vegetative	NP-V	2,218	19	3,393	21
	Flowering	NP-F	2,141	22	3,327	22
	Pod setting	NP-P	1,893	31	3,072	28
	Seed filling	NP-S	2,213	19	3,434	20

5.3.3. Estimated premium rates for area yield index insurance

Both simulated grain yield and yield reduction rate for each treatment were fitted in the equation (2) to obtain modified equation (2’) used to estimate the expected premium rate for each treatment (Table 22). The modified equation reads as follows:

$$(2') \quad Indem = \max\left[\left(\frac{y_c - y_i}{y_c}\right)(yfcast)(scale),\ 0\right]$$

Where: *yfcast* is the forecast area yield (i.e. grain yield for the control treatment),

y_c is the guaranteed or critical area yield [$y_c = yfcast$ *cov.] with cov. = 85%.

y_i is the actual area yield [$y_i = yfcast * \beta_i$], with β_i the yield decrease rate (%) due to the different weather stresses at vegetative, flowering, pod setting and seed filling stages, and *scale* representing the indemnity scale levels (80%, 90%, 100% and 110%).

For ease of presentation, indemnities are measured in kilograms per hectare instead of dollar (or Rwandan Francs) value per hectare. A hectare (ha) is a Rwandan local measure of area, 1 ha = 2.47 acre. To illustrate the interpretation of the calculated premium rates, a bean farmer would pay 231 or 282 kg ha^{-1} to obtain coverage of 80% of any shortfall of area bean yield due to drought stress at seed filling stage for bush and climbing bean, respectively.

The expected premium rate (EPR) varies substantially among the treatments for a given coverage level. The expected premium rates calculated for the 80% coverage level range from 0 kg ha^{-1} (DS-V) to 411 kg ha^{-1} (NP-P) for RW2245, and from 0 kg ha^{-1} (DS-V, DS-F) to 604 kg ha^{-1} for MAC44. The zero premium rates indicate that no yield shortfall exceeded 20% of the expected bean yield for the temporal drought stress at the specified crop growth stage.

As expected, EPR increases as coverage level increases for a given treatment. In general, the premiums are positively correlated at different coverage levels. Thus, a treatment with a high premium at the 80% indemnity level also has a high premium at the 110% coverage level. For the drought stress treatment, the highest expected premium rate was observed at seed filling stage and estimated at 231 kg ha^{-1} for RWR2245 and at 282 kg ha^{-1} for MAC44. Seed filling stages was the most sensitive to waterlogging with an expected premium rate of 334 kg ha^{-1} for RWR2245 and 523 kg ha^{-1} for MAC44. Pod setting stage was the most sensitive to natural bean disease pressure with expected premium rate of 411 kg ha^{-1} for RWR2245 and 523 kg ha^{-1} for MAC44.

With the yield reduction rates, expected premium rates for investigated treatments, at any defined yield coverage level, can be generated for any forecasted area yield. An example is presented in Appendix 4, where expected premium rates per hectare from the average bean yield of latest 5 years were estimated for the investigated treatments in the three study sites.

Table 22: [5.5] Estimated premium rates per hectare for area yield index insurance product

Bean type	Forecast Area Yield *"yfcast"*	Critical Area Yield (y_c) at $\alpha = 85\%$	TTT	Yield decrease rate in % (β)	Actual Area Mean Yield *"y"*	$Indem = \max\left[\left(\frac{y_c - y_i}{y_c}\right)(yfcast)(scale),\ 0\right]$			
						80%	90%	100%	110%
RWR2245 (bush)	2,729	2,320	DS-V	11	2,424	0	0	0	0
	2,729	2,320	DS-F	19	2,207	103	116	128	141
	2,729	2,320	DS-P	16	2,294	26	29	32	35
	2,729	2,320	DS-S	24	2,073	**231**	260	289	318
	2,729	2,320	WL-V	20	2,192	128	144	161	177
	2,729	2,320	WL-F	20	2,179	128	144	161	177
	2,729	2,320	WL-P	21	2,167	154	173	193	212
	2,729	2,320	WL-S	28	1,973	334	376	417	459
	2,729	2,320	NP-V	19	2,218	103	116	128	141
	2,729	2,320	NP-F	22	2,141	180	202	225	247
	2,729	2,320	NP-P	31	1,893	411	462	514	565
	2,729	2,320	NP-S	19	2,213	103	116	128	141
MAC44 (climbing)	4,278	3,636	DS-V	9	3,874	0	0	0	0
	4,278	3,636	DS-F	12	3,748	0	0	0	0
	4,278	3,636	DS-P	15	3,619	1	1	1	1
	4,278	3,636	DS-S	22	3,329	**282**	317	352	388
	4,278	3,636	WL-V	30	3,014	604	679	755	830
	4,278	3,636	WL-F	27	3,133	483	544	604	664
	4,278	3,636	WL-P	26	3,186	443	498	554	609
	4,278	3,636	WL-S	28	3,088	523	589	654	720
	4,278	3,636	NP-V	21	3,393	242	272	302	332
	4,278	3,636	NP-F	22	3,327	282	317	352	388
	4,278	3,636	NP-P	28	3,072	523	589	654	720
	4,278	3,636	NP-S	20	3,434	201	226	252	277

TTT = Treatment, DS=Drought stress, WL=Waterlogging, NP=No disease control measure, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling, Indem. = Indemnity

5.4. Discussion

5.4.1. Model calibration and validation

A part from the conservative parameters, whose values do not change, the two genotypes exhibited differences in all user-specific parameters used in the simulation. The CROPGRO-Dry bean model showed high sensitivity to variation in the genetic coefficients as the simulated yields varied under the same climate and soil conditions. This sensitivity could be associated with the differences in growth habit of the bean genotypes used in the experiment. As MAC44 is a climbing bean type and RWR2245 being bush bean type, it is obviously evident that the two genotypes could not have the same values for the growth and development parameters. Similarly, De Olivera *et al.* (2012) reported a high sensitivity of CROPGRO-Dry bean model to changes in the crop genetic coefficients for soybean and dry bean cultivars.

5.4.2. Simulated grain yields

CROPGRO-Dry bean model responded well to different levels of evaluated water stress treatments. For both drought and waterlogging, bean grain yield were simulated with relative root mean squared error (RRMSE) around 0.5 for both bush and climbing bean type. For a perfect fit, the RRMSE index ranges from 0 to infinity, with 0 corresponding to the ideal (Wu *et al.*, 2013). These low values of RRMSE indicated that the CROPGRO Dry bean model is accurate at predicting yield for both bush and climbing bean genotypes for the investigated water stress treatments. Therefore, this model can be used in predicting common bean yield losses for defined water related environmental stress. As reported by Boote *et al*. (2000) and Graef *et al.* (2012), process-oriented crop models such as CROPGRO-Soybean, CERES-Maize and CERES-Wheat have been used successfully to predict crop growth and yield under specified plant growing conditions.

The failure of the model to simulate variation in bean yield due to the pesticide application treatment could be attributed to the fact that the pest module of DSSAT operates with input of field-observed damage information or for field-measured pest populations rather than the number or time of pesticide application (Batchelor *et al.,* 2004). Boote *et al.* (2000) also found that the data collected on crop experiencing the pest damage were not very useful for model validation.

5.4.3. Estimated premium rates for area yield index insurance product

Higher expected premium rates were observed for drought, waterlogging and natural bean disease pressure at pod developmental stages (i.e. pod setting and seed filling). The high sensitivity of pod developmental stages to these weather related perils is attributed to the disturbance of the physiological functioning of plants during these plant growth stages. Darkwa *et al.* (2016) reported the decrease in photosynthate assimilation and poor carbohydrate partitioning to the developing grain as the reason of high yield reduction in grain yield due to water stress of common bean at reproductive stage. Furthermore, Ahmed *et al. (*2013) indicated that the greater sensitivity to water-stressed conditions at reproductive stage (pod development stage included), would be related to plant hormones, which increase dropping of flowers and/ or the loss of pod setting. Singh *et al.* (2013) also reported that this yield reduction is attributed to a decline in leaf conductance and C assimilation usually occurring within the first 1 to 3 days of imposition of flooding stress in *Phaseolus vulgaris.* Larger yield reductions when flooding is imposed at reproductive rather than vegetative growth stages have been reported for grain legume crops such as soybeans and mungbean (Lakitan *et al.*, 1992).

During the field experiments, the most observed diseases were angular leaf spot, ascochyta leaf spot, bean anthracnose and bean common mosaic virus (BCMV). These diseases may occur on any part of the plant above the ground during any stage of its life. However, symptoms of disease affecting leaves and pods are generally prominent during the late flowering and early pod formation stages (Buruchara *et al.,* 2010).

The least sensitivity of weather related stress at vegetative stage may be explained or attributed to a possible recovery of photosynthesis and leaf growth and low transpiration rate which may have resulted in a small reduction of grain yield and thus a small EPR in this study. The results of this study imply a certain recovering ability of dry bean from water stressed conditions. Ahmed *et al.* (2013) and Mukeshimana *et al.* (2014) reported that bean genotypes that wilted slowly were able to conserve water in leaves and stem tissues, survive the dry period, resume growth, and reproduce. Genotypes with lower wilting scores may have a mechanism to slow their transpiration rate and not deplete their soil moisture reserves as quickly as genotypes that have a high wilting score as was observed in soybean (Barrett *et al.,* 2007). This trait is known as "slow wilting" and has been identified and is being utilized in breeding for crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.) and soybean (*Glycine max* L.) for drought tolerance when grown under drought stress (Gebeyehu, 2006). Since genetic variation for the trait exists in soybean, there is an expectation that the same trait exists in dry bean. This trait relies on the interactions between hydraulic conductance in the leaves, the xylem and guard cells (Rezene *et al.,* 2011).

5.5. Conclusion

The effect of water stressed conditions and natural bean disease pressure on bean yield was associated with plant developmental stage at which the stress occurred. As evidenced in this research, the pod developmental stage (pod setting and seed filling) was the most sensitive to investigated weather related stresses (drought, waterlogging and natural bean disease pressure). Specifically seed filling stage was the most sensitive to both drought and waterlogging, whereas pod setting was highly affected by the natural bean disease pressure. Bean yield reduction rates were estimated based on the simulated grain yield for the defined weather related stresses throughout the plant developmental stages. Based on the estimated yield reduction losses, expected premium rates for an area yield index insurance product were estimated for the investigated weather perils at different plant growth stages of common bean. As the for the yield reduction rates, the expected premium rates were also higher for the weather related perils at pod developmental stage and estimated at 257 kg ha^{-1} for drought, 429 kg ha^{-1} for waterlogging and 467 kg ha^{-1} for natural bean disease pressure. Based on yield reduction rates, the study suggested an anticipated claim formula that can be used to estimate expected premium rates for an area yield index insurance model (AYII) for any forecasted area yield for drought, waterlogging and natural bean disease pressure at different plant growth stages. This study provides scientific knowledge and basis that can inform insurers to set up area yield index insurance sub-products targeting to cover weather related perils at different plant developmental stages with more focus on pod developmental stages.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1. General discussion

In Sub Saharan Africa (SSA), Index Based Crop Insurance (IBCI), Index Based Livestock Insurance (IBLI) and Area Yield Index Insurance (AYII) are the key products found either piloted or implemented. However, these products in general face low rates of adoption in the region due to their high premium rates. As indicated by Smith and Watts (2010), higher premium rates result in substantially lower levels of participation in agricultural insurance programs. Arshad *et al.* (2015) also reported that a unit increase in premium rate decreases the levels of participation in agricultural insurance programs by 0.03. The premium rates associated with the Area Yield Index Insurance is the most limiting factor to the product uptake that is offered as a full season cover contract against weather perils. Besides the premium payments do not consider bean plant growth and developmental stages. Nonetheless, greenhouse and field experiments depicted that, pod setting stage was severely affected by the waterlogging stress with a yield reduction of 28% whilst drought stress significantly affected bean production during seed filling stage with an estimated yield reduction of 23%. Pod setting stage was the most sensitive to natural bean disease pressure with an estimated yield loss of 30%. The corresponding modelled expected premium rates were estimated at 429 kg ha^{-1} for waterlogging stress at seed filling stage, 257 kg ha^{-1} for drought stress at seed filling and 467 kg ha^{-1} for natural bean disease pressure at pod setting.

The high susceptibility of these growth and developmental stages to weather perils is attributed to flower abscission, embryo abortion, and plant physiological disturbances (inhibition of photosynthesis, hampering both plant growth and plant development). According to Hatfield & Prueger (2015) and Mariani *et al.* (2010), water availability is one of the main limitations for dry bean (*Phaseolus vulgaris* L.) production and other crops worldwide. Both short duration and long-term water stress events with rainfall above or below the thresholds have the potential to cause considerable damage to crops and yields depending on their occurrence in the growing season (Wreford *et al.*, 2010). Exposure of dry bean plants to extreme water stress at the on-set of the reproductive stage has produced up to 60% less seed yield than those grown under no stressed conditions. Particularly, as climbing bean types continue to flower and fill pods from the start of flowering to almost the beginning of maturity, failure to receive adequate rainfall during flowering and pod fill will result in fewer flowers and pods on the plants (Gebeyehu, 2006).

Based on the yield reduction rates, the study has suggested an anticipated claim formula for estimating expected premiums rates for different plant growth stages, as a strategy to increase the uptake of AYII product. The increase in the product uptake was attributed to the relative low premium rates with sub-products targeting different plant developmental stages compared to the full cover insurance contract. According to Kong *et al.* (2011) and Lin *et al.* 2015), strategies of increasing uptake of AYII insurance scheme include lowering its associated premium rate through either lessening the cost of crop cutting experiments or improvement of the product design and delivery. Nganga (2013) and Wairimu *et al.* (2016) also reported that the three phase maize contracts covering the crop for drought stress at early growth, flowering and grain filling has increased the insurance product uptake in East Africa Countries.

This study has demonstrated that crop simulation models such as DSSAT can be used to enhance index-based insurance models as they are used to forecasting area or regional crop yields. Saseendran *et al.* (2015) and Huffman *et al.* (2015) reported that once a crop simulation model such as DSSAT is calibrated for a specific site, it can accurately simulate detailed yield components for specific crops. In addition, Deng *et al.* (2004) reported that index insurance based on predicted yields from the DSSAT model might have lower basis risk than index insurance based on a specific weather variable such as cooling degree days (CDD).

6.2. Conclusion

Agricultural insurance products have been identified as one of the recommended strategies to cope with climate related crop production constraints. Although data dependent, Area Yield Index Insurance (AYII) product insures multiple perils losses caused by weather risk, pests and diseases. Therefore, this product is the most relevant for limited resource farmers particularly in developing countries. Diversifying the Area Yield Index Insurance product into possible sub-products targeting the plant developmental stages could lead to a more robust and affordable insurance product. Field experiments and crop simulation with GROPGRO-Dry bean model of DSSAT were conducted to identify the most sensitive stages of common bean and inform insurers on which growth stages to focus most while tailoring an insurance contract to plant developmental stages. Pod setting stage was the most sensitive to natural bean disease pressure with an estimated yield loss of 30% and a corresponding expected premium rate of 467 kg ha^{-1}. Seed filling stage was the most sensitive to drought and waterlogging with an estimated yield reduction of 23% resulting in an expected premium rates of 257 kg ha^{-1}.

Seed filling was also highly affected by waterlogging with an estimated yield reduction of 28% and a corresponding premium rate of 429 kg ha^{-1}. Based on the bean yield loss rates, the study has suggested an anticipated claim formula for drought, waterlogging and natural bean disease pressure that could occur at different plant developmental stages. This will be a useful and innovative way of implementing the area yield index insurance product and will likely increase its uptake by resource limited farmers.

6.3. Recommendations

1. In the present study, the bean yield losses due to investigated treatments and corresponding expected premium rates were calculated assuming a temporal weather related stress (drought, waterlogging and natural bean disease pressure) observed once throughout the cropping season. Therefore, further studies may be necessary to assess bean yield losses and resulting premium rates in case of repetitive weather related stress throughout the cropping season.

2. The present study has suggested an anticipated claim formula to estimate actual area yield and premium rates for an AYII product for the investigated weather perils. As area yield index insurance product is defined for a specific geographical area (district or county) the current findings are site-specific. Therefore, additional similar studies may be required in other bean growing areas of Rwanda (districts) so as to have complete package for insuring bean farmers against weather related perils.

3. Index insurance products are often developed using both agricultural and climatic data. These data must be of high quality, relevant and timely available over a sufficiently long time horizon. Coordinated investments in agriculture and weather data should therefore be committed to make these data available on standards, reasonable terms to all insurance providers.

4. The most advantages of yield based index insurance products include capturing all agricultural perils (drought, excessive rainfall, pest and disease) although with high cost of crop cutting experiments. A combination of area yield data with satellite or weather data in place of crop cutting experiments can lead to an insurance product that offers both speed and reliability cost effectively.

5. Throughout the bean developmental stages, weather induced stresses led to different yield losses. Therefore, insurance providers should promote offering to farmers insurance products targeting plant developmental stages with more focus on pod developmental stage as the study depicted pod setting and seed filling more sensitive to weather related perils.

REFERENCES

Acosta-Diaz, E., Acosta-Gallegos, J. A., Trejo-López, C., Padilla-Ramirez, J. S. & Amador-Ramirez, M. D. (2009): Adaptation traits in dry bean cultivars grown under drought stress. *Agricultura Técnicaen México*, 35(4.1), 416-425.

ACRE Africa (2017): Report on Crop Cutting Exercise Conducted in Embu, Eastern Province of Kenya. Agriculture and Climate Risk Enterprise (ACRE-Africa), Nairobi, 22 pp.

ACRE Africa (2015): Implementation of Agricultural Insurance. Agriculture Finance Conference, Kigali, Rwanda. 14 pp.

AFR (2015): Report on Agricultural Finance Conference held in Kigali on 7-8 October 2015. Access to Finance Rwanda (AFR), Kigali, 28 pp.

Aggarwal, V. D., Pastor-Corrales, M. A., Chirwa, R. M. & Buruchara, R.A. (2004): Andean beans (*Phaseolus vulgaris*) with resistance to the angular leaf spot pathogen (*Phaeoisariopsis griseola*) in Southern and Eastern Africa. *Euphytica,* 136, 201–210.

Ahmed, A., Selim, M. M., Alderfasi, A. A. & Afzal, M. (2015): Effect of drought stress on mungbean (Vignaradiata L.) under arid climatic conditions of Saudi Arabia. *WIT Transactions on Ecology and The Environment*, 192, 1743-3541.

Ahmed, F., Rafil, M. Y., Ismail, M. R., Juraimi, A. S., Rahim, H. A., Asfaliza, R. & Latif, M. A. (2013): Waterlogging Tolerance of Crops: Breeding, Mechanism of Tolerance, Molecular Approaches, and Future Prospects. *BioMed Research International*, 1-10.

Aidoo, R., Mensah, O. J., Wie, P. & Awunyo-vitor, D. (2014): Prospects of crop insurance as a risk management tool among arable crop farmers in Ghana. *Asian Economic and Financial Review*, 4(3), 341-354.

Ambachew, D., Mekbib, F., Asfaw, A., Beebe, S. E. & Blair, M. W. (2015): Trait associations in common bean genotypes grown under drought stress and field infestation by BSM bean fly. *Crop Journal*, 3, 305–316.

Amri, M., El-Ouni, M. H. & Salem, M. B. (2015): Waterlogging affect the development, yield and components, chlorophyll content and chlorophyll fluorescence of six bread wheat genotypes (*Triticum aestivum L*.). *Bulgarian Journal of Agricultural Science*, 20 (3), 647-657.

ARC (2016): Africa Risk View End of Season Report, Senegal. Africa Risk Capacity (ARC), Available at www.africanriskcapacity.org. Accessed on 15th January 2017.

Arellanes, P. & Lee, D. (2003): The determinants of adoption of sustainable agriculture technologies: Evidence from the hillsides of Honduras. 2003 annual meeting, August 16-22, 2003, Durban, South Africa 25826, International Association of Agricultural Economists.

Arshad**,** M., Amjath-Babu, T. S., Kächele, H. & Müller, K. (2015): What drives the willingness to pay for crop insurance against extreme weather events (flood and drought) in Pakistan? A hypothetical market approach; http://dx.doi.org/10.1080/17565529.2015.1034232

Asare-Marfo, D., Birol, E., Gonzalez, C., Moursi, M., Perez, S., Schwarz, J. & Zeller, M. (2013): Prioritizing Countries for Biofortification Interventions Using Country-Level Data. HarvestPlus Working Paper N^{o}11

Asfaw, A. & Blair, M. W. (2014): Quantification of drought tolerance in Ethiopian common bean varieties. *The Journal of Agricultural Science,* 5, 124–139.

Ashraf M. A., (2012): Waterlogging stress in plants: A review. *African Journal of Agricultural Research,* 7(13), 1976-1981.

Backlund, P., Janetos, A., Schimel, D. & Walsh, M. (2008): The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, Washington, USA, 362 pp.

Bageant, E. R. & Barret, C. B. (2015): Are There Gender Differences in Demand for Index-Based Livestock Insurance? *The Journal of Development Studies*, 53 (6), 932–952.

Barnett, B. J. & Mahul, O. (2007): Weather index insurance for agriculture and rural areas in lower-income countries. *American Journal of Agricultural Economics*, 89 (5), 1241–1247.

Barnett, B. J., Black, J. R., Hu, Y. & Skees, J. R. (2005): Is Area Yield Insurance Competitive with Farm Yield Insurance? *Journal of Agricultural and Resource Economics,* 30(2), 285-301

Barrett, C. B., Barnett, B. J., Carter, M. R., Chantarat, S., Hansen, J. W., Mude, A. G., *et al.* (2007): Index Insurance for Climate Risk Management and Poverty Reduction, Technical Report.

Barrios, A. N., Hoogenboom, G., Nesmith, D. S. (2005): Drought stress and the distribution of vegetative and reproductive traits of a bean cultivar. *The Journal of Agricultural Science,* 62 (1), 18-22.

Batchelor, W. D., Jones, J. W., Boote, J. K. & Porter, C. H. (2004): Pest and Disease Damage Module in DSSAT v.4.0 Documentation and Source Code Listing. Research Report N^{o}2000-1205, University of Florida, Gainesville.

Bassanezi, R. B., Amorim, L., Bergamin Filho, A., Hau, B., & Berger, R. D. (2001): Accounting for photosynthetic efficiency of bean leaves with rust, angular leaf spot and anthracnose to assess crop damage. *Plant Pathology*, 50, 443-452.

Beebe, S. E., Rao, I. M., Cajiao, C., Grajales, C. M. (2008): Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. *Crop Science Journal*, 48, 582–592.

Beebe, S., Ramirez, J., Jarvis, A., Rao, I. M., Mosquera, G., Bueno, J. M. & Blair, M. W. (2011): Genetic Improvement of Common Beans and the Challenges of Climate Change. *Blackwell Publishing Ltd.*, 356-369.

Beebe, E. S., Rao, M. I., Blair, W. M. & Acosta-Gallegos, A. J. (2013): Phenotyping common beans for adaptation to drought. *Frontiers in Physiology,* 4, 1-20.

Bekele, S. & Tilahun, K. (2007): Regulated deficit irrigation scheduling of onion in a semi-arid region of Ethiopia. *Agriculture and Water Management Journal*, 89, 148-152.

Bergamin-Filho, A., Carneiro, S. M., Godoy, C. V., Amorim, L., Berger, R. D. & Hau, B. (1997): Angular leaf spot of Phaseolus beans: Relationships between disease, healthy leaf area, and yield. *Phytopathology,* 87, 506-515.

Binici, T. & Zulauf, R. (2006): Determining Wheat Crop Insurance Premium Based on Area Yield Insurance Scheme in Konya Province, Turkey; *Journal of Applied Science,* 6(5), 1148-1152.

Birachi, E. A., Ochieng, J., Wozemba, D., Ruraduma, C., Niyuhire, M. C. & Ochieng, D. (2011): Factors influencing smallholder farmers' bean production and supply to market in Burundi. *African Crop Science Journal*, 19(2), 335 – 342.

Blanco, L. J., Aguilera, M. O., Paruelo, J. M., & Biurrun F. N. (2008) : Grazing effect on NDVI across an aridity gradient in Argentina. *Journal of Arid Environments*, 72, 764–776

Boote, K. J., Jones, J. W., Hoogenboom, G., Batchelor, W. D., Porter, C. H. (2000): Plant Growth and Partitioning Module in DSSAT v4.0 Documentation and Source Code Listing. Research Report N^{o}2000-1204, University of Florida, Gainesville.

Borella, J., Do Amarante, L., De Oliveira, D. S., De Oliveira, A. C. B. & Braga, E. J. B (2014): Waterlogging-induced changes in fermentative metabolism in roots and nodules of soybean genotypes. *Scientia Agricola,* 71(6), 499-508

Bradford, K. J. (1983): Effects of soil flooding on leaf gas exchange of tomato plants. *Plant Physiology Journal*, 73, 475-479

Broughton, W. J., Hernandez, G., Blair, M., Beebe, S., Gepts, P. & Vanderleyden, J. (2003): Beans (Phaseolus spp.) – model food legumes. *Plant Soil,* 252, 55–128.

Buruchara, R., Mukankusi, C., Ampofo, K. & Walker, J. (2010): Bean disease and pest identification and management – Handbook for small scale seed producers. International Center for Tropical Agriculture (CIAT), Kawanda, 79 pp.

Buruchara, R., Hirwa, C., Sperling, L., Mukankusi, C., Rubyogo, J. C., Muthoni, R. & Abang, M. M, (2011): Development and delivery of bean varieties in Africa: The Pan- Africa Bean Research Alliance (PABRA) model. *African Crop Science Journal*, 19 (4), 227-245.

Calvache, M., Reichardt, K., Bacchp, O. S. & Dourado-Neto, D. (1997): Deficit irrigation at different growth stages of the common bean (*Phaseolus vulgaris L.*), *Scientia Agricola*, 54, 1-16.

Chantarat, S. (2009): Pro-Poor Risk Management: Essays on the economics of index-based risk transfer products. PhD Thesis, Cornell University, Ithaca, NY (USA).

Chantarat, S., Mude, G. A., Barrett, B. C. & Carter, R. M. (2011): Designing index based livestock insurance for managing asset risk in northern Kenya. *The Journal of Risk and Insurance,* 80 (1), 205–237.

Chilagane, L. A., Tryphone, G. M., Protas, D., Kweka, E., Kusolwa, P. M. & Nchimbi-Msolla, S. (2013): Incorporation of resistance to angular leaf spot and bean common mosaic necrosis virus diseases into adapted common bean (Phaseolus vulgaris L.) genotype in Tanzania. *African Journal of Biotechnology*, 12(27), 4343-4350.

Chunlei, W., Ruediger, A., & Youhua, M. (2013): Application of the DSSAT Model to Simulate Wheat Growth in Eastern China. *Journal of Agricultural Science,* 5 (5), 198-208.

CIAT (2004): CIAT Highlights in Africa-Enhancing Farmers' Access to Seed of Improved Bean Varieties in Rwanda. International Center for Tropical Agriculture (CIAT), Cali Columbia, 2 pp.

Cole. S., Bastian, G., Vyas, S., Wendel, C. & Stein, D. (2012): The effectiveness of index-based micro-insurance in helping smallholders manage weather-related risks. University of London, London, UK, 84 pp.

Cuellar-Ortiz, S. M., Arrieta-Montiel, M., Acosta-Gallegos, J. & Covartubias, A. A. (2008): Relationship between carbohydrate partitioning and drought resistance in common bean. *Plant, Cell and Environment*, 31, 1399–1409.

Cyamweshi, R. A., Tenywa, J. S., Makooma, M. T., Okiro, J. J., Dusengemungu, L., Mutimura, M. & Musoni, A. (2013): Farmers' Coping Mechanisms for Common Bean Production under Water-Logged Soil Conditions in Uganda-Rwanda Boarder Region. *Journal of Environmental Science and Engineering,* B.2, 46-52.

Dagnew, K., Haileselassie, T. & Feyissa, T. (2014): Genetic diversity studies of common bean (Phaseolus vulgaris L.) germoplasm from Ethiopia using inter simple sequence repeat (ISSR) markers. *African Journal of Biotechnology*, 13(36), 3638-3649.

Darkwa, K., Ambachew, D., Mohammed, H., Asfaw, A. & Blair, M. W. (2016): Evaluation of common bean (Phaseolus vulgaris L.) genotypes for drought stress adaptation in Ethiopia. *The Crop Journal, 4, 367-376*

Daron, J. D. & Stainforth, D. A. (2014): Assessing pricing assumptions for weather index insurance in a changing climate Climate Risk Management. Available at http://dx.doi.org/10.1016/j.crm.2014.01.001; Accessed on 22nd July 2017

Davis, J. G. & Brick, M. A. (2009): Fertilizing Dry Beans-Fact Sheet No. 0.539. Colorado State University, Colorado, USA, 3 pp.

Ddamulira, G., Mukankusi, C., Ochwo-Ssemakula, M., Edema, R., Sseruwagi, P. & Gepts, P. (2014): Identification of new sources of resistance to angular leaf spot among Uganda common bean landraces. *Canadian Journal of Plant Breeding*, 2(2), 55-65.

De Jesus Junior, W. C., Do-Vale, X. R., Coelho, R. R., Hau, B., Zambolim, L., Costa, L. C. & Bergamin Filho, A. (2001): Effects of Angular Leaf Spot and Rust on Yield Loss of *Phaseolus vulgaris. The American Phytopathological Society,* 91(11), 1045-1053

De Jesus Junior, W. C., Vale, X. R., Coelho, R. R., Paul, P. A., Hau, B., Bergamin Filho, A., *et al.* (2003): Relationships between angular leaf spot, healthy leaf area, effective leaf area and yield of *Phaseolus vulgaris*. *European Journal of Plant Pathology*, 109, 625–632.

De Oliveira, E. C., De Paula-Junior, T. J., Ferreira, W. P., Justino, F. B. & De Olivrea-Neves, L. (2012): The performance of the CROPGRO model for bean (*Phaseolus vulgaris L.*) yield simulation. *Acta Scientiarum Agronomy*, 34(3), 239-246.

Del Río, L. E., Bradley, C. A., Henson, R. A., Endres, G. J., Hanson, B. K., McKay, K., *et al.* (2007): Impact of Sclerotinia stem rot on yield of canola. *Plant Disease,* 91, 191-194.

Deng, X., Barnett, B. J., Yu, Y., and Hoogenboom, G. (2004): Managing Crop Production Risk with Crop Index Insurance Products. Selected Paper prepared for presentation at the Southern Agricultural Economics Association Annual Little Rock, Arkansas, February 5-9, 2004

Dercon, S., Hill, R. V., Clarke, D., Outes-Leon, I. & Taffesse, A. S. (2014): Offering rainfall insurance to informal insurance groups: Evidence from a field experiment in Ethiopia. *Journal of Development Economics*, 106, 132–143

Dick, W., Stoppa, A., Anderson, J., Coleman, E. & Rispoli, F. (2011): Weather Index-based Insurance in Agricultural Development, A Technical Guide, International Fund for Agricultural Development (IFAD), Rome, Italy, 61 pp.

Edward, W. & Plastina, A. (2014): Revenue Protection Crop Insurance, Extension and Outreach. Iowa State University of Science and Technology, Ames, Iowa, 4 pp.

Efetha, A. (2011): Irrigation Scheduling for Dry Bean in Southern Alberta. Alberta Ag-Info Centre, available at www.agriculture.alberta.ca, accessed on 2nd February, 2018.

Eitzinger, A., Läderach, P., Rodriguez, B., Fisher, M., Rizo, L. & Ocon, S. (2012): Tortillas on the roaster: Central American maize-bean systems and the changing climate. International Centre for Tropical Agriculture (CIAT), Cali, Colombia.

Emam, Y. & Seghatoleslami, M. J. (2005): Crop Yield: Physiology and Processes. First edition. Shiraz University Inc., Shiraz, 593 pp.

Emam, Y., Shekoofa, A., Salehi, F. & Jalali, A. H. (2010): Water Stress Effects on Two Common Bean Cultivars with Contrasting Growth Habits. *American-Eurasian J. Agric. & Environ.* Sci., 9 (5), 495-499.

FAO (2011): Statistical database of the Food and Agriculture Organisation of the United Nations, Rome, Italy, http://faoatat.fao.org

Foster, T., Brozovic, N., Butler, A. P., Neale, M. U., Raes, D., Steduto, P., *et al.* (2017): AquaCrop-OS: An open source version of FAO's crop water productivity model. *Agricultural Water Management*, 181, 18–22

FSD-Kenya (2013): Review of FSD's index based weather insurance initiatives. Financial Sector Deepening Kenya (FSD-Kenya), Nairobi, 60 pp.

Gallenstein, R., Mishra, K., Sam, A. & Miranda, M. (2015): Willingness to Pay for Insured Loans in Northern Ghana. Selected Paper prepared for presentation at the 2015 Agricultural & Applied Eoconomics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-28

Gebeyehu, S. (2006): Physiological Response to Drought Stress of Common Bean (*Phaseolus vulgaris L.*) Genotypes Differing in Drought Resistance. PhD Thesis, Universidad de Liebig-Giessen, Giessen, Germany, 131 pp.

Giertz, A., Mudahar, M. S., Gray, G., Rubaiza, R., Galperin, D. & Suit, K. (2015): Rwanda Agricultural Sector Risk Assessment. World Bank Group Report N^{o}96290-RW, 120 pp.

Giné, X. & Yang, D. (2009): Insurance, credit and technology adoption: Field experimental evidence from Malawi. *Journal of Development Economics*, 89, 1–11

Goodwin, P.H. (1992): Effect of common bacterial blight on leaf photosynthesis of bean. *Canadian Journal of Plant Pathology*, 14, 203–206.

Graeff, S., Link, J., Binder, J. & Claupein, W. (2012): Crop Models as Decision Support Systems in Crop Production Available at http://www.intechopen.com ; accessed on 20th July, 2016

Graham, P. H. & Ranalli, P. (1997): Common Bean (Phaseolus vulgaris L.). *Field Crops Research*, 53, 131-146.

Greatrex, H, Hansen, J. W, Garvin, S., Diro, R., Blakeley, S., Le Guen, M., *et al.* (2015): Scaling up index insurance for smallholder farmers: Recent evidence and insights. CCAFS Report No. 14, Copenhagen, Available online at: www.ccafs.cgiar.org

GSMA (2015): State of the Industry Report 2014-2015: Mobile Financial Services for the Unbanked, available at www.gsma.com/mobilemoney, accessed on 11th May 2017.

Hatfield, J. L. & Prueger, J. H. (2015): Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes,* 10, 4–10

Hazell, P., Anderson, J., Balzer, N., Clemmensen, H. A., Hess, U. & Rome, R. F. (2010): The Potential for Scale and Sustainability in Weather Index Insurance for Agriculture and Rural Livelihoods. International Fund for Agricultural Development (IFAD) and World Food Programme, 153 pp.

Hengl, T., Mendes de Jesus J., Heuvelink, B. M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., *et al.* (2017): SoilGrids250m: Global gridded soil information based on machine learning. *PLoS ONE,* 12(2), 1-40.

Hill, R. V. (2010): Agricultural insurance in Sub-Saharan Africa: can it work? Paper prepared for the Fourth African Agricultural Markets Program (AAMP) policy symposium, Lilongwe, Malawi, September 6-10, 2010.

Hillocks, R. J., Madata, C. S., Chirwa, R., Minja, E. M. & Msolla, S. (2006): Phaseolus bean improvement in Tanzania 1959-2005. *Euphytica,* 150, 225-231.

Hoogenboom, G., Jones, J. W., Porter, C. H., Wilkens, P. W., Boote, K. J., Hunt, L. A., Tsuji, G. Y. (2010): Decision Support System for Agro-technology Transfer Version 4.5. Volume 1: Overview; University of Hawai, Honolulu, HI.

Horneck, D. A., Sullivan, D. M., Owen, J. S. & Hart, J. M. (2011): Soil Test Interpretation Guide. Oregon State University, Corvallis, 12 pp.

Hossain, M. B., Rahman, M. W., Rahman, M. N., Anwar, A. H. M. N. & Hossen, A. K. M. (2010): Effects of water stress on yield attributes and yield of different Mungbean genotypes. *International Journal of Sustainable Crop Production,* 5(1), 19-24.

Houk, E., Frasier, M. & Schuck, E. (2004): The regional effects of waterlogging and soil salinization on a rural county in the Arkansas River Basin of Colorado. Selected paper presented at the Western Agricultural Economics Association Annual Meeting, Honolulu, HI. June 30 - July 2, 2004.

Huffman, T., Qian, B., 1, De Jong, R., Liu, J., Wang, H., McConkey, B., et al. (2015): Upscaling modelled crop yields to regional scale: A case study using DSSAT for spring wheat on the Canadian prairies. *Canadian Journal of Soil Science,* 95, 49-61

Jackson, M. B. (1990): Hormones and developmental change in plants subjected to submergence or soil waterlogging. *Aquatic Botany,* 38, 49-72

Jensen, N. D., Barret, C. B. & Mude A. G. (2015): The favorable impacts of index-based livestock insurance: Evaluation results from Ethiopia & Kenya. Research Brief 52. International Livestock Research Institute (ILRI), Nairobi, 4 pp.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L.A., *et al.* (2003): The DSSAT cropping system model. *European Journal of Agronomy,* 18, 235-265.

Katungi, E., Farrow, A., Chianu, J., Sperling, L. & Beebe, S. (2009): Common bean in Eastern and Southern Africa: A situation and outlook analysis. International Center for Tropical Agriculture (CIAT), Cali, Colombia, 61 pp.

Kalima, S. P. (2013): Physiological responses of common bean (*Phaseolus vulgaris* L.) genotypes to water stress. MSc Thesis , University of Zambia, 91 pp.

Katungi, E., Farrow, A., Mutuoki, T., Gebeyehu, S., Karanja, D., Alemayehu, F. *et al.* (2010): Improving common bean productivity: An analysis of socio-economic factors in Ethiopia and Eastern Kenya. International Center for Tropical Agriculture, Cali, Columbia (CIAT), 140 pp.

Kevane, M. (2011): Gendered production and consumption in rural Africa. *Proceedings of the National Academy of Sciences of the United States of America*, 109 (31), 12350–12355.

Khan, M. I. & Walker, D. (2015): Application of Crop Growth Simulation Models in Agriculture with special reference to Water Management Planning. *International Journal of Core Engineering & Management*; 2(5): 113-130.

Kimani, P. M., Buruchara, R., Ampofo, K., Pyndji, M., Chirwa, R. M., & Kirkby, R. (2001): Breeding Beans for Smallholder Farmers in Eastern, Central, and Southern Africa: Constraints, Achievements, and Potential. PABRA Millennium Workshop, Arusha, Tanzania, 28 May – 1 June 2001

Koloma, Y. (2015): Crop Microinsurance for Maize Farmers in Burkina Faso: Access and Agriculture Performance in the Dandé Village. *Strategic Change*, 24, 115–129.

Kong, R., Turvey, C. G., Rong, K., Guangwen, H., Jiujie, M. & Patrick, M. (2011): Factors influencing Shaanxi and Gansu farmers' willingness to purchase weather insurance. *China Agricultural Economic Review*, 3(4), 423 – 440.

Kumar, S., Niwas, R., Khichar, M. L., Singh, A., Yogest, K. & Abdilash (2017): Genetic Coefficient and Validation of DSSAT for Cotton under Different Growing Environments. *International Journal of Current Microbiology and Applied Science, 6*(4), 1031-1041.

Lakitan, B., Wolfe, D. W. & Zobel, R. W. (1992): Flooding Affects Snap Bean Yield and Genotypic Variation in Leaf Gas Exchange and Root Growth Response. *J. Amer. Soc. Hort. Sci.* 117(5):711-716.

Larochelle, C. & Alwang, J. (2014): Impacts of Improved Bean Varieties on Food Security in Rwanda. Selected Paper presented at the 2014 Annual Meeting of the Agricultural & Applied Economics Association, Minneapolis, July 27-29, 2014.

Larochelle, C., Asare-Marfo, D., Birol, E., & Alwang, J. (2015): Assessing the Adoption of Improved Bean Varieties in Rwanda and the Role of Varietal Attributes in Adoption Decisions. HarvestPlus, Working Paper No25.

Larochelle, C., Asare-Marfo, D., Birol, E., & Alwang, J. (2016): Assessing the Adoption of Improved Bean Varieties in Rwanda and the Role of Varietal Attributes in Adoption Decisions. HarvestPlus, Working Paper N^{o}25.

Leblois, A., Quirion, P. & Sultan, B. (2014): Price vs. weather shock hedging for cash crops: Ex ante evaluation for cotton producers in Cameroon. *Ecological Economics*, 101, 67–80.

Lemessa, F., Sori, W. & Wakjira, M. (2011): Association of angular leaf spot (Phaeoisariopsi griseola (Sacc) Ferraris) and common bean (*Phaseolus vulgaris*) yield loss at Jimma, Southwestern Ethiopia. *Plant pathology Journal*, 10(2), 57-65.

Li, Y. P., You, M. P., Colmer, T. D., & Barbetti, M. J. (2015): Effect of timing and duration of soil saturation on soilborne *Pythium* diseases of common bean (*Phaseolus vulgaris*). *Plant Disease Journal*, 99, 112-118.

Lin, J., Boyd, M., Pai, J., Porth, L., Zhang, Q. & Wang, K. (2015): Factors affecting farmers' willingness to purchase weather index insurance in the Hainan Province of China. *Agricultural Finance Review*, 75 (1), 103 – 113.

Liu, J., Men, C., Cabrera, E. V., Uryasev, S. & Fraisse, C. W. (2007): Optimizing Crop Insurance under Climate Variability. University of Florida, Gainesville, 27pp.

Lopes, D. B. & Berger, R. D. (2000): The effects of rust and anthracnose on the photosynthetic competence of diseased bean leaves. *Phytopathology*, 91, 212-220.

Lunze, L., Abang, M. M., Buruchara, R., Ugen, M. A., Nabahungu, N. L., Rachier, *et al.* (2012): Integrated Soil Fertility Management in Bean-Based Cropping Systems of Eastern, Central and Southern Africa, Soil Fertility Improvement and Integrated Nutrient Management – A global Perspective, *InTech,* 239-273 pp.

Mahul, O., Belete, N. & Goodland, A. (2009): Innovations in Insuring the Poor: Index-based Livestock Insurance in Mongolia. In: Hill, R. V. & Torero, M. Innovations in Insuring the Poor. International Food Policy Research Institute (IFPRI), Washington, 40 pp.

Mahul, O., Verma, N. & Clarke, J. D. (2012): Improving Farmers' Access to Agricultural Insurance in India. The World Bank, Washington, 22 pp.

Mariani, L., Garcia, A., Hansen, J. W. & Nain, A. S. (2010): Weather and climate forecasts for agriculture. *ResearchGate*, 58 pp.

Mavric, I. & Sustar-Vozlic, J. (2004): Virus diseases and resistance to bean common mosaic and bean common mosaic necrosis potyvirus in common bean (*Phaseolus vulgaris L.*). *Acta agriculturae slovenica,* 83(1), 181-190.

Mbonigaba, J. J., Nzeyimana, I., Bucagu, C. & Culot, M. (2009): Caractérisation physique, chimique et microbiologique de trois sols acides tropicaux du Rwanda sous jachères naturelles et contraintes à leur productivité. *Biotechnology, Agronomy, Society and Environment*, 13(4), 545-558

McFarlane, N. M, Ciavarella, T. A, Smith, K. (2003): The effect of waterlogging on growth, photosynthesis and biomass allocation in perennial ryegrass (*Lolium perenne*) genotypes with contrasting root development. *Journal of Agricultural Science,* 141, 241-248.

McPeak, J., Chantarat, S. & Mude, A. (2010): Explaining index-based livestock insurance to pastoralists. *ReserachGate*, 38 pp.

Mensah, N. O., Fialor, S. C. & Yeboah, E. (2017): Evaluating the Constraints to Development of Agricultural Insurance for Cashew Crop Farmers in Brong-Ahafo Region of Ghana. *Open Journal of Business and Management*, 5, 215-229.

Meronuck, R., Wright, J. & Rehm, G. (2016): Integrated Pest Management control of white mold in irrigated dry beans/Soil water monitoring methods. University of Minnesota Extension, available at www.extension.umn.edu, accessed on 9th October, 2016.

Mersha, Z & Hau, B. (2011): Reciprocal effects of host and disease dynamics in the bean rust pathosystem. *Journal of Plant Diseases and Protection*, 118 (2), 54–62.

Miorini, T. J. & Saad, C. J. (2012): Productivity and Water Suppression in Different Beans (Phaseolus vulgaris L) Phenological Stages. Sao Paulo State University, Brazil, 5 pp.

Miranda, M. J. (1991): Area-Yield Crop Insurance Reconsidered. *American Journal of Agricultural Economics*, 73(2), 233-242.

Miranda, M. J. & Mulangu, F. M. (2016): Index Insurance for Agricultural Transformation in Africa. African Transformation Report 2016: Transforming Africa's Agriculture, 58 pp.

Moorhead, A., Chater, C. & Hoel, A. (2009): Climate, agriculture and food security: A strategy for change. Consultative Group on International Agricultural Research (CGIAR), 56 pp.

Mude, G. A., Chantarat, S., Barrett, C. B., Carter, R. M., Ikegami, M. & McPeak, G. J. (2010): Insuring Against Drought Related Livestock Mortality: Piloting Index Based Livestock Insurance in Northern Kenya. International Livestock Research Institute (ILRI), Nairobi.

Mudingu, J. (2017): With climbing beans, farmers are climbing out of poverty, nutritional insecurity. The New Times, Kigali, 5 pp.

Mugambi, C. (2016): Mobile money and insurance in Africa: What's the connection? http://www.blog.kpmgafrica.com, accessed on 5th May 2017

Mukankusi, C. M., Melis, R., Derera, J., Laing, M. & Buruchara, R. (2008): Improving resistance to Fusarium root rot [Fusarium solani (Mart.) Sacc.f.spphaseoli (Burkholder) W.C. Snyder & H.N. Hans.] in common bean (Phaseolus vulgaris L.). PhD Thesis, University of KwaZulu-Natal, 201 pp.

Mukeshimana, G., Lasley, A. L., Loescher, W. H. & Kelly, J. D. (2014): Identification of shoot traits related to drought tolerance in common bean seedlings. *Journal of American Society of Horticultural Science,* 139(3), 299-309.

Muñoz-Perea, C. G., Allen, R. G., Westermann, D. T., Wright, J. L., Singh, S. P. (2007): Water use efficiency among dry bean landraces and cultivars in drought-stressed and non-stressed environments. *Euphytica*, 155, 393–402.

Musoni, A., Kimani, P., Narla, R. D., Buruchara, R. & Kelly, J. (2010): Inheritance of fusarium wilts (Fusarium oxysporum F. sp. phaseoli) resistance in climbing beans. *African Journal of Agricultural Research*, 5(5), 399-404.

Musoni, A., Butare, L., Mukankubana, D., Murwanashyaka, E., Kabeja, A., Rumongi, A., *et al.* (2012): Released iron dense, high yielding, disease tolerant and marketable climbing and bush bean varieties, Rwanda Agriculture Board, Kigali, 34 pp.

Mutoni, R. A. & Andrade, R. (2015): The Performance of Bean Improvement Improvement Programmes in Sub-Saharan Africa from the Perspectives of Varietal Output and Adoption. CGIAR and CAB International, 148-163 pp.

Mwang'ombe, A. W., Wagara, I. N., Kimenju, J. W. & Buruchara, R. A., (2007): Occurrence and Severity of Angular Leaf Spot of Common Bean in Kenya as Influenced by Geographical Location, Altitude and Agro-ecological Zones. *Plant pathology Journal*, 6(3), 235-241.

Nieto, J. D., Cook, S., Lundy, M., Fisher, M., Sanchez, D. & Guevara, E. (2006): A system of drought insurance for poverty alleviation in rural areas; Final report, 94 pp.

Nkalubo, S., Melis, R., Laing, M. D. & Opio, F. (1997): Yield loss associated with anthracnose disease on Ugandan market-class dry bean cultivars. *African Crop Science Conference Proceedings,* 8, 869-874.

Nganga, R. (2013): Model of insurance in Africa. Selected paper presented at the CCAFS Workshop on Institutions and Policies to Scale out Climate Smart Agriculture held between 2-5 December 2013, Colombo, Sri Lanka.

Ntukamazina, N., Onwonga, N. R., Sommer, R., Rubyogo, J. C., Mukankusi, C. M., Mburu, J. & Kariuki, R. (2017): Index-based agricultural insurance products: challenges, opportunities and prospects for uptake in sub-Sahara Africa. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 118(2), 171-185

Ochieng, J., Niyuhire, M. C., Ruraduma, C., Birachi, E. & Ouma, E. (2014): Bean Utilization and Commercialization in Great Lakes Region of Central Africa: The Case of Smallholder Farmers in Burundi. *ResearchGate*, 295-306 pp.

Odening, M. & Shen, Z. (2014): Challenges of insuring weather risk in agriculture. *Agricultural Finance Review*, 74 (2), 188 – 199.

Olango, N., Tusiime, G., Mulumba, J. W., Nankya, R., Fadda, C., Jarvis, D. I., & Paparu, P. (2016): Response of Ugandan common bean varieties to *Pseudocercospora griseola* and angular leaf spot disease development in varietal mixtures. *International Journal of Pest Management*, 63(2), 119-127.

Osdaghi, E., Alizadeh, A., Shams-Bakhsh, M. & Reza, L. M. (2009): Evaluation of common bean lines for their reaction to the common bacterial blight pathogen. *Phytopathologia Mediterranea,* 48, 461–468.

Osipenko, M., Shen, Z. & Odening, M. (2015): Is there a demand for multi-year crop insurance? *Agricultural Finance Review*; 75(1), 92 – 102.

Ostyula, R. M. (2010): Nature of genetic control and inheritance of resistance to pythium root rot in bean genotypes. PhD Thesis, Makerere University, Kawanda, Uganda, 103 pp.

Otieno, P. E., Muthomi, J. W., Chemining'wa, G. N. & Nderitu, J. H. (2007): Effect of rhizobia inoculation, farmyard manure and nitrogen fertilizer on growth, nodulation and yield of selected food grain legumes. African Crop Science Conference Proceedings, 8, 305-312.

Pamela, P., Mawejje, D. & Ugen, M. (2014): Severity of angular leaf spot and rust diseases on common bean in Central Uganda. *Uganda Journal of Agricultural Sciences*, 15(1), 63-72.

Pataky, J. K., Raid, R. N., Du Toit, L. J. & Schueneman, T. J. (1998): Disease severity and yield of sweet corn hybrids with resistance to northern leaf blight. *Plant Disease*, 82, 57-63.

Polania, J. A., Poschenrieder, C., Beebe, S. & Rao, I. M. (2016): Effective Use of Water and Increased Dry Matter Partitioned to Grain Contribute to Yield of Common Bean Improved for Drought Resistance. *Frontiers in Plant Science*, 7, 1-10.

Raju, S. S. & Chand, R. (2008): Agricultural Insurance in India: Problems and Prospects. National Centre for Agricultural Economics and Policy Research, Working Paper N^{o} 8.

Ramirez-Vallejo, P. & Kelly, J. D. (1998): Traits related to drought resistance in common bean, *Euphytica*, 99, 127–136.

Rao, K. N. (2010): Index based Crop Insurance; *Agriculture and Agricultural Science Procedia*, 1, 193–203.

Rezene, Y., Gebeyehu, S. and Zelleke, H. (2011): Genetic variation for drought resistance in small red seeded common bean genotypes. *Afr. Crop. Sci. J.* 19, 303–312.

Rezzoug, W., Gabrielle, B., Suleiman, A. & Benabdeli, K. (2008): Application and evaluation of the DSSAT-wheat in the Tiaret region of Algeria. *African Journal of Agricultural Research,* 3 (4), 284-296.

Riche, C. J. (2004): Identification of soybean cultivars tolerance to waterlogging through analyses of leaf nitrogen concentration. MSc Thesis, Louisiana State University, 42 pp.

Rosales, M. A., Ocampo, E., Rodríguez-Valentín, R., Olvera-Carrillo, Y., Acosta-Gallegos, J. & Covarrubias, A. A. (2012): Physiological analysis of common bean (Phaseolus vulgaris L.) cultivars uncovers characteristics related to terminal drought resistance. *Plant Physiology and Biochemistry,* 56, 24-34.

Rushemuka, P. N., Bock, L., Mowo, J. G. (2014): Soil science and agricultural development in Rwanda: state of the art - A review. *Biotechnology, Agronomy, Society and Environment* 18(1), 142-154.

Sadeghipour, O. (2008): Effect of withholding irrigation at Different Growth Stages on Yield and Yield Component of Mungbean (*Vigna radiate L*) Varieties. *American-Eurasian Journal of Agriculture & Environment Science,* 4(5), 590-594.

Samboko, P. C. (2011): An assessment of factors influencing the profitability of bean production in Zambia. BSc. Dissertation, University of Zambia, 39 pp.

Saseendran, S. A., Ma, L., Malone, R., Heilman, P., Ahuja, L. R., Kanwar, R. S., Karlen, D. L. & Hoogenboom, G. (2015): Simulating management effects on crop production, tile drainage, and water quality using RZWQM–DSSAT. *Geoderma* 140, 297–309

Schwartz, H. F., Correa, V. F., Pineda, P. A., Otoya, M. M., & Katherman, M. J. (1981): Dry bean yield losses caused by Aschochyta, angular and white leaf spots in Colombia. *Plant Disease,* 65, 494-496.

Scott, H. D., DeAngulo, J., Daniels, M. B., Wood, L. S. (1989): Flood duration effects on soybean growth and yield. *Agronomy Journal,* 81, 631-636.

Skees, J. R., Black, J. R. & Barnett, B. J. (1997): Designing and Rating an Area Yield Crop Insurance Contract. *American Journal of Agricultural Economics*, 79(2), 430-438.

Skees, J. R. & Barnett, B. J. (2006): Enhancing microfinance using index-based risk-transfer products. *Agricultural Finance Review,* 66 (2), 235 – 250.

Sheppard, J. & Hoyle, F., (2016): Water availability/Fact sheet. Department of Agriculture and Food, Western Australia (online), accessed on 27th October 2016.

Singh, S. P. (2001): Broadening the genetic base of common bean cultivars. *Crop Science Journal*, 41, 1659-1675.

Singh, A. K., Goyal, V., Mishra, A. K. & Parihar, S.S. (2013): Validation of CropSyst simulation model for direct seeded rice–wheat cropping system. *Current Science*, 104(10), 1324-1331.

Singh, P. K., Singh, K. K., Rathore, L. S., Baxla, A. K., Bhan, S. C., Gupta, A., *et al.* (2016): Rice (Oryza sativa L.) yield gap using the CERES-rice model of climate variability for different agroclimatic zones of India. *Current science*, 110(3), 405-413.

Smith, H. V. & Watts, M. (2010): Index Based Agricultural Insurance in Developing Countries: Feasibility, Scalability and Sustainability. Montana State University, Bozeman, 40 pp.

Sperling, L. & Munyaneza, S. (1995): Intensifying production among smallholder farmers: The impact of improved climbing beans in Rwanda. *African Crop Science Journal*, 3(1), 117-125.

Stoeffler, Q., Gelade, W., Guirkinger, C., & Carter, M. (2016): Indirect protection: the impact of cotton insurance on farmers' income portfolio in Burkina Faso. Selected Paper presented at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2, 2016.

Tao, F., Yokozawa, M. & Zhang, Z. (2009): Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization and uncertainties analysis, *Agricultural and forest meteorology 149, 831–850.*

Tadesse, M. A., Shiferaw, B. A. & Erenstein, O. (2015): Weather index insurance for managing drought risk in smallholder agriculture: lessons and policy implications for sub-Saharan Africa. *Agricultural and Food Economics*, 3(26), 1-21.

Takahashi, K., Ikegami, M., Sheahan, M. & Barret, C. B. (2016): Experimental Evidence on the Drivers of Index-Based Livestock Insurance Demand in Southern Ethiopia. *World Development*, 78, 324–340.

Toai, T. T., Hoa, T. T., Hue, N. T., Nguyen, H. T., Shannon, J. G. & Rahman, M. A. (2010): Flooding Tolerance of Soybean [*Glycine max* (L) Merr] Germplasm from Southeast Asia under Field and Screen-House Environments. *The Open Agriculture Journal*, 4, 38-46.

Trought, M. C. T. & Drew, M. C. (1980): The development of waterlogging damage in wheat seedlings (*Triticum aestivum L.*) I. Shoot and root growth in relation to changes in concentration of dissolved gases and solutes in the soil solutions. *Plant Soil*, 54, 77- 94.

Tryphone, G. M., Chilagane, L. A., Kusolwa, P. M., Nchimbi-Msolla, S. (2012): Inheritance of Angular leaf spot (*Phaeosariopsis griseola*) resistance in common bean (*Phaseolus vulgaris*) population. *Journal of Agriculture Science and Technology*, 2(7), 586-862.

Uddin, S., Parvin, S. & Awal, M. A. (2013): Morpho-physiological aspects of mungbean (vignaradiata L.) in response to water stress. *International Journal of Agricultural Science and Research*, 3 (2), 137-148.

Van Schoonhoven, A. & Pastor-Corrales, M. A. (1987): Standard system for the evaluation of bean germplasm. International Centre for Tropical Agriculture (CIAT), Cali, Columbia

Verdoodt, A., VanRanst, E. & Ye, L. (2004): Daily Simulation of Potential Dry Matter Production of Annual Field Crops in Tropical Environments. *Agronomy Journal*, 96, 1739–1753.

Verdoodt, A & Rast, E. V (2006): The soil information system of Rwanda: A useful tool to identify guidelines towards sustainable land management. *Afrika Focus*, 19 (1-2), 69-92.

VSN International (2011): GenStat for Windows 14th Edition.VSN International, Hemel Hempstead, UK. Web page: GenStat.co.uk

Wahome, S. W., Kimani, P. M., Muthomi, J. W., Narla, R. D. & Buruchara, R. (2011): Multiple disease resistance bean genotypes in Kenya. *African Crop Science Journal*, 19(4), 289 – 302.

Wagara, I. N., Mwang'ombe, A. W., Kimenju, J. W. & Buruchara, R. A. (2005): Virulence, variability and physiological races of the angular leaf spot pathogen Phaeoisariopsis griseolicola in Kenya. *African Plant Protection*, 11, 23-31.

Wairimu, E., Obare, G. & Odendo, M. (2016): Factors affecting weather index-based crop insurance in Laikipia County, Kenya. *Academic Journals*, 8 (7), 111–121.

Wasonga, J., Marcial, C., Pastor-Corrales, A., Timothy, G., Porch, P. and Griffiths, D. (2010): Targeting gene combinations for broadspectrum rust resistance in heat-tolerant snap beans developed for tropical environments. *Journal of American Society of Horticulture Science*, 135(6), 521-532.

World Bank (2009): Index-based Crop Insurance in Senegal: Promoting Access to Agricultural Insurance for Small Farmers. Washington, DC, 104 pp.

World Bank (2010): Agricultural Insurance in Latin America: Developing the Market. Report no. 61963-Latin America and Caribb, Washington, DC, 152 pp.

World Bank (2011): Nigeria Crop Weather Index Insurance Pre-Feasibility Study Report. Washington, DC, 139 pp.

World Bank (2015): Achievements in ACP Countries by Global Index Insurance Facility (GIFF) Program: Phase 1 (2010-2015). Global Index Insurance Facility (GIFF), Washington, DC, 50 pp.

Worrall, E. A., Wamonje, F. O., Mukeshimana, G., Harvey, J. W., Carr, J. P., Mitter, N. (2015): Bean Common Mosaic Virus and Bean Common Mosaic Necrosis Virus: Relationships, Biology, and Prospects for Control. *Advances in Virus Research*, 93, 1-47.

Worthmann, C. S., Kirkby, R. A., Elude, C. A. & Allen, D.J. (1998): Atlas of Common Bean (*Phaseolus vulgaris L.);* Production in Africa. International Center for Tropical Agriculture (CIAT), CIAT Publ., 297:63.

Wortman, C. S. (1992): Assessment of yield loss caused by biotic stress on beans in Africa. International Center for Tropical Agriculture (CIAT), Occasional publications series, N^{o}4

Wreford, A., Moran, D. & Adger, N. (2010): Climate Change and Agriculture: Impacts, adaptation and mitigation; Organization for Economic Co-operation and Development (OECD), 140 pp.

Wu, C., Anlauf, R. & Ma, Y. (2013): Application of the DSSAT Model to Simulate Wheat Growth in Eastern China. *Journal of Agricultural Science*, 5(5), 1-77.

Zhang, J. & Davies, W. J. (1987): ABA in roots and leaves of flooded pea plants. *Journal of Experimental Botany*, 38, 649-659.

APPENDICES

Appendix 1: ANOVA tables for effect of water stress on agronomic performance of common bean

RWR 2245

Number of days to flowering

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	81.955	8.195	5.24	<.001
Site	1	51.011	51.011	32.61	<.001
Treatment .Site	10	41.864	4.186	2.68	0.008
Residual	66	103.25	1.564		
Total	87	278.08			

Number of days to physiological maturity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	868.068	86.807	13.5	<.001
Site	1	106.92	106.92	16.63	<.001
Treatment .Site	10	177.205	17.72	2.76	0.007
Residual	66	424.25	6.428		
Total	87	1576.44			

Plant height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	690.02	69	2.27	0.024
Site	1	1489.14	1489.14	48.91	<.001
Treatment .Site	10	2136.61	213.66	7.02	<.001
Residual	66	2009.5	30.45		
Total	87	6325.27			

Number of pods per plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	777.75	77.775	8.26	<.001
Site	1	2684.05	2684.05	285.03	<.001
Treatment .Site	10	843.205	84.32	8.95	<.001
Residual	66	621.5	9.417		
Total	87	4926.5			

MAC44

Number of days to flowering

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	250.591	25.059	5.76	<.001
Site	1	290.909	290.909	66.9	<.001
Treatment .Site	10	77.091	7.709	1.77	0.083
Residual	66	287	4.348		
Total	87	905.591			

Number of days to physiological maturity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	1150.25	115.025	18.02	<.001
Site	1	33.136	33.136	5.19	0.026
Treatment .Site	10	104.614	10.461	1.64	0.116
Residual	64	408.5	6.383		
Total	85	1680.52			

Plant height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	6862.3	686.2	0.85	0.579
Site	1	140161	140161	174.45	<.001
Treatment .Site	10	35686.3	3568.6	4.44	<.001
Residual	66	53028	803.5		
Total	87	235737			

Number of pods per plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	146.9	14.69	0.83	0.603
Site	1	1144.32	1144.32	64.52	<.001
Treatment .Site	10	289.57	28.96	1.63	0.118
Residual	64	1135.17	17.74		
Total	85	2669.72			

RWR2245

Number of grains per pod

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	7.0699	0.707	2.49	0.013
Site	1	14.309	14.309	50.39	<.001
Treatment .Site	10	8.1672	0.8167	2.88	0.005
Residual	66	18.7409	0.284		
Total	87	48.287			

Weight of 100 grains

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	1283.57	128.36	3.01	0.003
Site	1	7.44	7.44	0.17	0.678
Treatment .Site	10	449.14	44.91	1.05	0.411
Residual	66	2817.87	42.7		
Total	87	4558.03			

Grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	382.35	38.23	2.71	0.008
Site	1	4583.68	4583.68	324.37	<.001
Treatment .Site	10	702.43	70.24	4.97	<.001
Residual	66	932.66	14.13		
Total	87	6601.11			

MAC44

Number of grains per pod

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	42.7769	4.2777	5.85	<.001
Site	1	26.86	26.86	36.76	<.001
Treatment .Site	10	11.491	1.1491	1.57	0.135
Residual	64	46.7609	0.7306		
Total	85	122.403			

Weight of 100 grains

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	3030.1	303	2.21	0.028
Site	1	12675.9	12675.9	92.49	<.001
Treatment .Site	10	4441.1	444.1	3.24	0.002
Residual	65	8908.3	137.1		
Total	86	29030.9			

Grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	10	867.76	86.78	3.15	0.003
Site	1	1956.23	1956.23	71.06	<.001
Treatment .Site	10	661.32	66.13	2.4	0.017
Residual	65	1789.45	27.53		
Total	86	5179.66			

Appendix 2: ANOVA tables for effect of natural bean disease pressure on yield of common bean

Bush bean genotypes

Bugesera

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate	3	22175528	7391843	2.59	
Variety	1	329216	329216	0.12	0.757
Treatment	7	2202532	314647	4.17	<0.001
Variety .Treatment	7	147606	21087	0.28	0.954
Residual	21	9932979	2933980	9.38	
Total	39	34787861			

Huye

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate	6	31155412	5192569	9.35	
Variety	1	507738	507738	0.91	0.376
Treatment	7	3030636	432948	8.16	<.001
Variety .Treatment	7	137709	19673	0.37	0.914
Residual	48	5562370	608641	3.04	
Total	69	40393865			

Musanze

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate	8	96754179	12094272	9.04	
Variety	1	3402569	3402569	2.54	0.149
Treatment	7	6072340	867477	14.5	<.001
Variety .Treatment	7	261557	37365	0.62	0.734
Residual	58	3469955	59827		
Total	81	109960600			

Climbing bean genotypes

Bugesera

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate stratum	3	21129310	7043103	16.05	
Variety	1	7143391	7143391	16.28	0.027
Treatment	7	1432845	204692	7.7	0.003
Variety .Treatment	7	361373	51625	1.94	0.121
Residual	21	1794863	465415	1.18	
Total	39	31861782			

Huye

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate stratum	6	12007183	2001197	8.77	
Variety	1	435235	435235	1.91	0.216
Treatment	7	6036991	862427	14.83	<.001
Variety .Treatment	7	103025	14718	0.25	0.968
Residual	48	3811558	286230	2.2	
Total	69	22393992			

Musanze

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replicate	8	103121993	12890249	35.15	
Variety	1	387621	387621	1.06	0.334
Treatment	7	8617338	1231048	6.93	<.001
Variety .Treatment	7	1318782	188397	1.06	0.401
Residual	58	13240408	544406	1.14	
Total	81	126686142			

Appendix 3: Observed and predicted grain yield (kg ha^{-1}) for the thee study sites

Bean Type	Treatment		BUGESERA			HUYE			MUSANZE		
	#	ID	Obs.	Sim.	RRMSE	Obs.	Sim.	RRMSE	Obs.	Sim.	RRMSE
RWR2245 (bush)	1	Control	3,639	2,702	0.292	3,639	2,397	0.368	3,639	3,438	0.149
	2	DS-V	3,011	2,383	0.224	3,011	2,378	0.225	3,011	2,609	0.156
	3	DS-F	3,218	2,145	0.365	3,218	2,135	0.368	3,218	2,613	0.239
	4	DS-P	2,407	1,849	0.397	2,407	2,097	0.348	2,407	3,218	0.467
	5	DS-S	3,203	2,009	0.375	3,203	1,434	0.554	3,203	3,079	0.055
	6	WL-V	1,969	1,973	0.309	1,969	1,759	0.327	1,969	3,139	0.670
	7	WL-F	3,375	2,065	0.394	3,375	1,951	0.427	3,375	2,710	0.209
	8	WL-P	3,068	2,100	0.413	3,068	1,949	0.452	3,068	2,571	0.312
	9	WL-S	3,113	1,735	0.462	3,113	2,012	0.378	3,113	2,400	0.265
	10	NP-V	2,117	2,702	0.497	1,445	2,397	0.742	1,899	3,438	0.821
	11	NP-F	1,663	2,702	0.724	1,430	2,397	0.756	2,666	3,438	0.483
	12	NP-P	1,501	2,702	0.994	1,043	2,397	1.305	2,194	3,438	0.702
	13	NP-S	1,990	2,702	0.495	1,211	2,397	1.005	2,810	3,438	0.311
MAC44 (climbing)	1	Control	5,498	4,150	0.248	5,498	4,097	0.258	5,498	4,930	0.110
	2	DS-V	4,343	3,917	0.106	4,343	3,608	0.174	4,343	4,440	0.046
	3	DS-F	4,446	3,658	0.211	4,446	3,339	0.274	4,446	4,549	0.116
	4	DS-P	4,719	3,531	0.270	4,719	3,060	0.365	4,719	4,623	0.100
	5	DS-S	4,538	2,883	0.370	4,538	2,591	0.434	4,538	4,874	0.098
	6	WL-V	3,243	2,643	0.205	3,243	801	0.758	3,243	5,084	0.575
	7	WL-F	2,882	3,947	0.447	2,882	982	0.706	2,882	5,157	0.828
	8	WL-P	4,216	3,759	0.214	4,216	1,113	0.759	4,216	5,034	0.268
	9	WL-S	3,648	3,461	0.158	3,648	1,277	0.667	3,648	4,989	0.397
	10	NP-V	1,607	4,150	1.634	1,157	4,097	2.560	2,258	4,930	1.222
	11	NP-F	1,416	4,150	1.982	1,419	4,097	1.898	2,646	4,930	0.923
	12	NP-P	1,314	4,150	2.246	1,509	4,097	1.745	1,835	4,930	1.759
	13	NP-S	1,717	4,150	1.439	1,396	4,097	1.946	2,719	4,930	0.820

DS=Drought stress, WL=Waterlogging, NP=No disease control measure, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling, Obs. = Observed, Sim.= Simulated, RRMSE = Relative root mean square error

Appendix 4: Expected premium rates per hectare from 5-years historical bean yield data

4.1. Bugesera District

	Crop	Common bean (*Phaseolus vulgaris L.*)					
	Years	2016	2015	2014	2013	2012	Average
Yield (kg ha^{-1})	Bush	665	662	854	661	484	665
	Climbing	965	1131	1197	832	739	973

Forecast area yiled (kg ha^{-1})	Coverage level	Trigger yield (kg ha^{-1})
665	85%	565
973	85%	827

Expected premium rates for each treatment (kg ha^{-1})

Bean type	Forecast Area Yield *"yfcast"*	Critical Area Yield (y_c) at α = 85%	Treatment	Yield decrease rate (%)	Actual Area Mean Yield *"y"*	$Indem = \max\left[\left(\frac{y_c - y_i}{y_c}\right)(yfcast)(scale),\ 0\right]$			
						80%	90%	100%	110%
Bush	**665**	565	DS-V	11	592	0	0	0	0
	665	565	DS-F	19	539	25	28	31	34
	665	565	DS-P	16	559	6	7	8	9
	665	565	DS-S	24	505	56	63	70	77
	665	565	WL-V	20	532	31	35	39	43
	665	565	WL-F	20	532	31	35	39	43
	665	565	WL-P	21	525	38	42	47	52
	665	565	WL-S	28	479	81	92	102	112
	665	565	NP-V	19	539	25	28	31	34
	665	565	NP-F	22	519	44	49	55	60
	665	565	NP-P	31	459	100	113	125	138
	665	565	NP-S	19	539	25	28	31	34
Climbing	**973**	924	DS-V	9	885	33	37	41	45
	973	924	DS-F	12	856	57	65	72	79
	973	924	DS-P	15	827	82	92	102	113
	973	924	DS-S	22	759	139	157	174	192
	973	924	WL-V	30	681	205	230	256	282
	973	924	WL-F	27	710	180	203	225	248
	973	924	WL-P	26	720	172	194	215	237
	973	924	WL-S	28	701	188	212	236	259
	973	924	NP-V	21	769	131	147	164	180
	973	924	NP-F	22	759	139	157	174	192
	973	924	NP-P	28	701	188	212	236	259
	973	924	NP-S	20	778	123	138	154	169

DS=Drought stress, WL=Waterlogging, NP=No pesticide use, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling, Indem. = Indemnity

4.2. Huye District

	Crop	Common bean (*Phaseolus vulgaris L.)*					
	Years	2016	2015	2014	2013	2012	Average
Yield (kg ha^{-1})	Bush	635	632	815	704	772	712
	Climbing	921	1079	1143	725	429	859

Forecast area yield (kg ha^{-1})	Coverage level	Trigger yield (kg ha^{-1})
712	85%	605
859	85%	730

Expected premium rates for each treatment (kg ha^{-1})

Bean type	Forecast Area Yield *"yfcast"*	Critical Area Yield (y_c) at α = 85%	Treatment	Yield decrease rate (%)	Actual Area Mean Yield *"y"*	$Indem = \max\left[\left(\frac{y_c - y_i}{y_c}\right)(yfcast)(scale),\ 0\right]$			
						80%	90%	100%	110%
Bush	**712**	605	DS-V	11	634	0	0	0	0
	712	605	DS-F	19	577	27	30	34	37
	712	605	DS-P	16	598	7	8	8	9
	712	605	DS-S	24	541	60	68	75	83
	712	605	WL-V	20	570	34	38	42	46
	712	605	WL-F	20	570	34	38	42	46
	712	605	WL-P	21	562	40	45	50	55
	712	605	WL-S	28	513	87	98	109	120
	712	605	NP-V	19	577	27	30	34	37
	712	605	NP-F	22	555	47	53	59	64
	712	605	NP-P	31	491	107	121	134	147
	712	605	NP-S	19	577	27	30	34	37
Climbing	**859**	816	DS-V	9	782	29	33	36	40
	859	816	DS-F	12	756	51	57	63	70
	859	816	DS-P	15	730	72	81	90	99
	859	816	DS-S	22	670	123	138	154	169
	859	816	WL-V	30	601	181	203	226	249
	859	816	WL-F	27	627	159	179	199	219
	859	816	WL-P	26	636	152	171	190	209
	859	816	WL-S	28	618	166	187	208	229
	859	816	NP-V	21	679	116	130	145	159
	859	816	NP-F	22	670	123	138	154	169
	859	816	NP-P	28	618	166	187	208	229
	859	816	NP-S	20	687	109	122	136	149

DS=Drought stress, WL=Waterlogging, NP=No disease control measure, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling, Indem. = Indemnity

4.3. Musanze District

	Crop	Common bean (*Phaseolus vulgaris L.*)					
	Years	2016	2015	2014	2013	2012	Average
Yield (kg ha^{-1})	Bush	907	903	1164	686	795	891
	Climbing	1316	1541	1633	1026	895	1282

Forecast area yield (kg ha^{-1})	Coverage level	Trigger yield (kg ha^{-1})
891	85%	757
1282	85%	1090

Expected premium rates for each treatment (kg ha^{-1})

Bean type	Forecast Area Yield *"yfcast"*	Critical Area Yield (y_c) at α = 85%	Treatment	Yield decrease rate (%)	Actual Area Mean Yield *"y"*	$Indem = \max\left[\left(\frac{y_c - y_i}{y_c}\right)(yfcast)(scale),\ 0\right]$			
						80%	90%	100%	110%
Bush	**891**	757	DS-V	11	793	0	0	0	0
	891	757	DS-F	19	722	34	38	42	46
	891	757	DS-P	16	748	8	9	10	12
	891	757	DS-S	24	677	75	85	94	104
	891	757	WL-V	20	713	42	47	52	58
	891	757	WL-F	20	713	42	47	52	58
	891	757	WL-P	21	704	50	57	63	69
	891	757	WL-S	28	642	109	123	136	150
	891	757	NP-V	19	722	34	38	42	46
	891	757	NP-F	22	695	59	66	73	81
	891	757	NP-P	31	615	134	151	168	184
	891	757	NP-S	19	722	34	38	42	46
Climbing	**1,282**	1,218	DS-V	9	1,167	43	49	54	59
	1,282	1,218	DS-F	12	1,128	76	85	94	104
	1,282	1,218	DS-P	15	1,090	108	121	135	148
	1,282	1,218	DS-S	22	1,000	184	206	229	252
	1,282	1,218	WL-V	30	897	270	304	337	371
	1,282	1,218	WL-F	27	936	238	267	297	327
	1,282	1,218	WL-P	26	949	227	255	283	312
	1,282	1,218	WL-S	28	923	248	279	310	341
	1,282	1,218	NP-V	21	1,013	173	194	216	238
	1,282	1,218	NP-F	22	1,000	184	206	229	252
	1,282	1,218	NP-P	28	923	248	279	310	341
	1,282	1,218	NP-S	20	1,026	162	182	202	223

DS=Drought stress, WL=Waterlogging, NP=No disease control measure, V=Vegetative, F=Flowering, P=Pod setting, S=Seed filling, Indem. = Indemnity