WATER USE AND NUTRITIONAL WATER PRODUCTIVITY OF SELECTED MAJOR AND UNDERUTILISED GRAIN LEGUMES

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa through WRC Project No. K5/2493//4 "Water use and nutritional water productivity of food crops for improved nutrition and health in poor rural households."

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate. As accepted by the University of KwaZulu-Natal, this thesis is in the form of published, accepted and submitted journal articles, which are indicated in each chapter.

Signed: Supervisor

Date: 26 February 2018

DECLARATION

I, Tendai Polite Chibarabada, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

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(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

SIGNATURE

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DEDICATION

This thesis is dedicated to my late father

ABSTRACT

Grain legumes have potential to alleviate the prevalence of food and nutrition security in water scarce areas. There is need to promote underutilised grain legumes to diversify crop production and build resilience. This requires knowledge on their water use (ET), environmental adaptation and nutritional content (NC) in comparison to major legumes. The study benchmarked underutilised grain legumes [bambara groundnut (*Vigna subterranea*) and cowpea (*Vigna unguiculata*)] to major grain legumes [groundnut (*Arachis hypogaea*) and dry bean (*Phaseolus vulgaris*)] with respect to ET, water productivity (WP), NC and nutritional water productivity (NWP). Field experiments were conducted during the 2015/16 and 2016/17 summer seasons under varying water regimes [optimum irrigation (OI), deficit irrigation (DI) and rainfed (RF)] and environmental conditions (Ukulinga, Fountainhill and Umbumbulu) in KwaZulu-Natal, South Africa. Data collected included stomatal conductance, leaf area index, timing of key phenological stages and yield. Water use was calculated as a residual of the soil water balance. Water productivity was calculated as the quotient of grain yield and ET. Grain was analysed for protein, fat, Ca, Fe and Zn. Yield, ET and NC were used to compute NWP. Results from the field trials were used calibrate and test the performance of AquaCrop model for groundnut and dry bean. Under varying water regimes, crops adapted to limited soil water through stomatal regulation and reduction in canopy size and duration. Yield, yield components and WP varied significantly ($P < 0.05$) among crop species. During 2015/16, groundnut had the highest yield and WP under DI (10 540 kg ha^{-1} and 0.99 kg m^{-3}, respectively). During 2016/17, the highest yield and WP were observed in dry bean under DI (2 911 kg ha^{-1} and 0.75 kg m^{-3}, respectively). For both seasons, dry bean had the lowest ET across all water treatments (143 – 268 mm). Dry bean and groundnut out–performed bambara groundnut with respect to yield, harvest index and WP. Yield varied significantly ($P < 0.05$) across environments and seasons. Cowpea was the most stable species. Results of NWP were significant among crops ($P < 0.05$). Yield instability caused fluctuations in NWP. Groundnut had the highest NWP$_{\text{fat}}$ (46 – 406 g m^{-3}). Groundnut and dry bean had the highest NWP$_{\text{protein}}$ (29 – 314 g m^{-3}). For NWP$_{\text{Fe, Zn and Ca,}}$ dry bean and cowpea were more productive. Overall, the AquaCrop model was successfully calibrated for groundnut and dry beans. Model testing showed AquaCrop's potential for simulating growth, yield and ET of groundnut and dry bean under semi-arid conditions. Underutilised grain legumes need to undergo crop improvement for successful promotion. There is need to improve adaptation of grain legumes to different environments and resilience to extreme weather events. Future studies should consider benchmarking more underutilised grain legumes to major grain legumes.

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CHAPTER 1

GENERAL INTRODUCTION AND OVERVIEW

1.1 General Introduction and Conceptualisation

Approximately two billion people around the world, suffer from some form of malnutrition (International Food Policy Research Institute [IFPRI], 2016). Malnutrition refers to deficiencies, excesses or imbalances in a person's intake of energy and/or nutrients. Of these two billion people, most them reside in the semi-and arid regions of the world (south Asia and sub-Saharan Africa). It is estimated that in these regions 15% and 23% of the populations, respectively suffer from some form of malnutrition (IFPRI, 2016). With the projected trends of population growth in these regions this number is likely to increase. It is also in these regions that approximately 70% of the population depends on agriculture for their food and livelihood (Alliance for a Green Revolution in Africa [AGRA], 2014). Attempts on improving food security in semi– and arid tropics have focussed on increasing production of cereals and root and tuber crops which are staple crops in these regions. Staple crops have received significant research and government attention (Organisation for Economic Co-operation and Development [OECD]; Food and Agriculture Organization [FAO], 2015). In most of these areas, cereals are locally available and cheaper and are a priority when incomes are not sufficient to meet the needs of a high quality diverse diet (United Nations Development Programme [UNDP], 2012).

Staples crops have a role to play in ensuring adequate calorie intake, but they are poor sources of other nutrients. This may also explain why the prevalence of malnutrition is high in the semi- and arid tropics. There is need for a balance between starch rich foods and other nutrient rich foods to improve dietary quality (Chibarabada et al., 2017). Meat is the main source of protein while vegetables are the main source of vitamins and minerals. The availability and accessibility of meat and vegetables is unsustainable for the rural households. Grain legumes enhance nutritional status of cereal based diets because they are a good source of protein, low saturated fat, carbohydrates, fibre as well as micronutrients (zinc, iron and calcium) (Tharanathan and Mahadevamma, 2003). Despite the nutritional benefits of grain legumes, they have not yet been fully adopted in cropping systems**.**

There is need to promote grain legumes in cropping systems to improve dietary diversity and alleviate malnutrition. There are more than 40 edible species of grain legumes yet only a few species are commonly grown in the semi- and arid tropics (Chibarabada et al., 2017). Of the common grain legumes consumed in the semi-and arid tropics, majority of them are exotic species [groundnut (*Arachis hypogaea*), dry bean (*Phaseolus vulgaris*) and soybean (*Glycine max*). Underutilised grain legumes that have a long history of cultivation in the semi- and arid tropics have since been neglected. With issues of crop diversification and increasing resilience of rural cropping systems, lies an opportunity to reintroduce underutilised grain legumes. However, any successful reintroduction of underutilised grain legumes requires information on how they compare to major grain legumes as this influences their uptake by farmers.

Agricultural production is limited by water availability as these regions suffer from some form of water scarcity (Seckler et al., 1999). There is need to increase food production to alleviate malnutrition and cater for the growing population. Increasing food production cannot be met through increasing irrigation. As such, strategies to improve water productivity (WP) have become a necessity for poor farmers living in semi– and arid tropics (Molden et al., 2010). Promotion of grain legumes, will require information on how they adapt to semi– and arid areas. For effective recommendations there is need for consideration of a water-food-nutrition-health nexus approach. This implies use of indices that consider water, yield and nutrition. Nutritional water productivity (NWP) has been proposed as useful metric for quantifying yield and nutrition outcomes per unit of water consumed. There is also a need to adopt crop modelling as a tool to answer research questions, thus, limiting time and resources spent on carrying out field experiments under various environments and management.

1.2 Aims and objectives

It was hypothesised that there are no differences between major and underutilised grain legumes with respect to adaptation, yield, productivity, nutritional content and nutritional water productivity. The study was aimed at benchmarking underutilised grain legumes to major grain legumes with respect to adaptation, water use and productivity, nutritional content (NC) and nutritional water productivity (NWP) under different production scenarios. The specific objectives were;

1. To provide a holistic perspective on the potential of legumes,

2. To conduct a comparative analysis of adaptation, yield, water use and WP of a selected underutilised and major grain legumes under different water regimes,

3. To determine the species × environment interaction as well as yield stability analysis of selected underutilised and major grain legumes

4. To determine nutrient content and NWP of selected underutilised and major grain legumes under different production environments and
5. To calibrate and test the performance of AquaCrop model for groundnut and dry bean in a semi – arid environment.

Thesis structure

The thesis is written in paper format and comprises seven chapters which are each standalone but linked to the objectives. Five of them are manuscripts and where the manuscript has been published or is under review in a particular journal, such details are provided in the footnote of the title page.

Chapter 1 is the current chapter that seeks to provide the background and aims and objectives of the study.

Chapter 2 is a review of literature that seeks to address the first objective. The literature review used the value chain approach to identify opportunities and challenges for successful promotion of grain legumes. The literature review was also used for selection of major and underutilised grain legumes to be used for the study.

Chapter 3 reports on the second objective. The chapter reports on growth (leaf area index), physiology (stomatal conductance), yield, water use and productivity of three grain legumes (bambara groundnut, groundnut and dry bean) under three water regimes (rainfed, deficit and optimum irrigation). The chapter further reports on desirable attributes contributing to yield of the different grain legumes using path coefficient analysis.

Chapter 4 reports on species * environment effect of four grain legumes (bambara groundnut, groundnut, cowpea and dry bean. The chapter reports on their adaptation (phenology, yield, water use and productivity) across the different environments under rainfed scenarios.

Chapter 5 reports on nutritional content and NWP of three grain legume (bambara groundnut, groundnut, dry bean and cowpea) under varying water regimes and in response to varying production environments.

Chapter 6 addresses the fifth objective of the study. The FAO's AquaCrop model was used. The first season results (2015/16) from the water treatments were used to calibrate the model for groundnut and dry bean. Results from the 2016/17 season of the water treatments and different environments were then used to test the performance of the model.

Chapter 7 is the general discussion, that integrates the separate manuscripts to address thesis objectives. It provides the major findings of the thesis and further recommends future research and important technical considerations in planning research.

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CHAPTER 2

EXPOUNDING THE VALUE OF GRAIN LEGUMES IN THE SEMI- AND ARID TROPICS

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Abstract

Approximately 70% of the population in the semi- and arid tropics reside in rural areas and depend on agriculture for their livelihood. Crop production is primarily focused on a few starchy staple crops. While this can ensure adequate calories, it inadvertently neglects the need for dietary diversity. Consequently, food and nutritional insecurity remains prevalent in the semi- and arid tropics. We reviewed the legume value chain with the aim to identify opportunities and challenges to unlocking their value and promoting them in the tropics. Several grain legumes are rich in proteins and micronutrients. They also possess adaptability to marginal environmental conditions such as drought and low input systems which typify rural landscapes. Adaptability to abiotic stresses such as drought makes them key to agriculture in areas that will receive less rainfall in the future. However, this potential was currently not being realized due to a range of challenges. Aspects related to their seed systems, production, post-harvest handling and marketing remain relatively under-researched. This was especially true for minor legumes. There is a need for trans-disciplinary research which will address the entire value chain, as has been done for major starchy crops. This could also unlock significant economic opportunities for marginalized groups such as women. This will unlock their value and allow them to contribute meaningfully to food and nutrition security as well as sustainable and resilient cropping systems.

Keywords: food and nutritional insecurity; South Asia; sub-Saharan Africa; value chain; water scarcity

1.1. Introduction

Water scarcity is increasing, and this is exacerbated by population growth and ongoing climate change and variability (Conway et al., 2009). Most of the regions categorized as ‘water scarce’ lie in the semi- and arid tropics. It is also in these regions that approximately 70% of the population depends on agriculture for their food and livelihood (Alliance for a Green Revolution in Africa (AGRA), 2013; Graeub et al., 2015). The prevalence of food and nutritional insecurity in semi- and arid tropics also remains high. South Asia and sub-Saharan Africa (SSA) have the highest estimated number of individuals experiencing some form of undernutrition (281 million and 224 million, respectively) (FAO et al., 2015). This represents about 15% and 23% of the respective populations of South Asia and SSA. These figures are expected to increase due to population growth and climate change. The 2014/15 and 2015/16 drought that was experienced across SSA due to El Niño placed more than 30 million people at risk of hunger, with children being most vulnerable (UNICEF, 2015). There is a need for a paradigm shift in terms of how we address challenges of food and nutrition security (Mabhaudhi et al., 2016)]. Part of this includes identifying and promoting the cultivation of crops that are most suited to these environments. Such crops should also have the inherent capacity to contribute to the resilience of farming systems in these areas.

Across much of the semi- and arid tropics, cereals (rice (*Oryza sativa*)), maize (*Zea mays*) and wheat (*Triticum* spp.) and root and tuber crops (cassava (*Manihot esculenta*)), Irish potato (*Solanum tuberosum*) and sweet potato (*Ipomea batatas*) are the staple crops. These crops have been the subject of significant research and government attention (OECD and FAO, 2015). This has led to breeding of high-yielding and drought-tolerant cultivars of common cereals and root and tuber crops. Cereals and root and tuber crops, which are starch rich, mainly provide calories to address energy requirements but lack dietary diversity to ensure adequate nutrition (Kearney, 2010). Dietary diversity is a strategy that involves including a variety of food groups to the diet such as fruit and vegetables, legumes, starch and animal products (Faber et al., 2002). Meat, fruit and vegetables are the major sources of proteins and micronutrients, respectively, but they are not always accessible to the rural poor. Meat remains expensive while fruit and vegetables are generally affordable, only when in season, but unaffordable when out of season. In this regard, the use of grain legumes as alternative sources of protein and other micronutrients (Iqbal et al., 2006) could assist in improving dietary diversity of poor rural households.

The promotion of grain legumes has been mainly linked to them being rich sources of protein, low in saturated fat, as well as possessing certain important micronutrients (zinc, folate and calcium and tocopherols) (Akinyele and Shokunbi, 2015; Boschin and Arnoldi, 2011;

Seena and Sridhar, 2005). In this regard, legumes could contribute significantly to diets of rural households if consumed as compliments to starch. While history shows that early Khoikhoi and Indian settlers in the semi- and arid tropics utilized indigenous legumes as a major component of their diets (Mooney and Drake, 2012), this status has since changed. The "Green Revolution" shifted attention to cereal crops. While this resulted in improvements to crop production and energy supply, it inadvertently resulted in stagnation of production and crop improvement of legumes (Pingali, 2012). The promotion of legumes which are adapted to the semi- and arid tropics will contribute to the diversity of cropping systems and diets of people living in these areas. However, there is need to address critical knowledge gaps that will allow for the promotion and reinstatement of legumes within food systems.

To date, there has been separate attempts by crop scientists (Chibarabada et al., 2015; Mabhaudhi et al., 2013; Muñoz-Perea et al., 2007; Obalum et al., 2011; Patel et al., 2008; Siddique et al., 2001; Zhang et al., 2000) and nutritionists (Akinyele and Shokunbi, 2015; Boschin and Arnoldi, 2011; Seena and Sridhar, 2005) to address the knowledge gap on legumes. These efforts have been disciplinary and the information is yet to be consolidated so as to make meaningful impact on policy. The emerging interest on minor legumes, indigenous to semi- and arid tropics, should also be considered (Chivenge et al., 2015). As the world celebrated the International Year of Pulses in 2016, there was a need to re-conceptualize the possible role that legumes can play in the post-2015 agenda. The aim of this review was to provide a holistic perspective on the potential of legumes. This was done through focusing on the legume value chain and identifying challenges and opportunities for unlocking the value of legumes.

A mixed-method review approach, which included combining quantitative and qualitative research or outcomes with process studies, was used to compile the review. Scientific journal articles, book chapters, technical reports and other forms of literature were used for the review. The review focused primarily on literature describing sub-Saharan Africa and South Asia; the two regions share similar development trajectories, challenges and opportunities, thus making them comparable. The review was then structured as follows; Section 1.2 provides an overview of water scarcity in SSA and SA and its effect on agricultural production. Furthermore, Section 1.2 also highlights food and nutritional security status in SSA and SA using selected indicators such as stunting, wasting, anemia and obesity. Section 1.3 discusses grain legumes, with a focus on their diversity and adaptability to the semi- and arid tropics. Section 1.4 discusses the progress and gaps in research on grain legumes. A value chain approach was used to categorize research into four components, namely, (i) breeding and crop improvement; (ii) agronomy; (iii) processing and utilization; and (iv) marketing. Lastly, Sections 1.5 and 1.6 present the challenges, opportunities and recommendations concerning promoting legumes in semi- and arid tropics.

1.2 Setting the Scene – South Asia and Sub-Saharan Africa

South Asia refers to the southern part of Asia which is dominated by the Indian tectonic plate which rises above sea level as Nepal and extends to the south of the Himalayas and the Hindu Kush. Sub-Saharan Africa refers to the regions that are fully or partially located south of the Sahara Desert. The two regions are climatically alike according to the Köppen-Geiger climate classification. They are described as semi- and arid climates due to actual precipitation being less than actual evapotranspiration (Peel et al., 2007). These two regions are also considered the poorest regions in the world (Wojcicki, 2014). Approximately 70% of the population in these regions reside in rural areas and rely on agriculture for their food and livelihood (www.worldbank.org). However, agricultural activities are primarily challenged by water scarcity.

1.2.1. Water Scarcity

Most countries in South Asia and sub-Saharan Africa experience some form of water scarcity (Figure 1). Rainfed agriculture is the primary source of food production in the semi- and arid tropics. The amount of arable land under rainfed production ranges from 60% to 95% (Rockström et al., 2010); making water is the most limiting factor in crop production. The uncertainties in rainfall distribution and occurrences and the high frequency of dry spells and droughts (Rockström, 2003) frequently result in significant yield losses and crop failure for rural farmers. Most of them are incapable of recovering from such disturbances. This alludes to the importance of promoting resilient cropping systems in these areas.

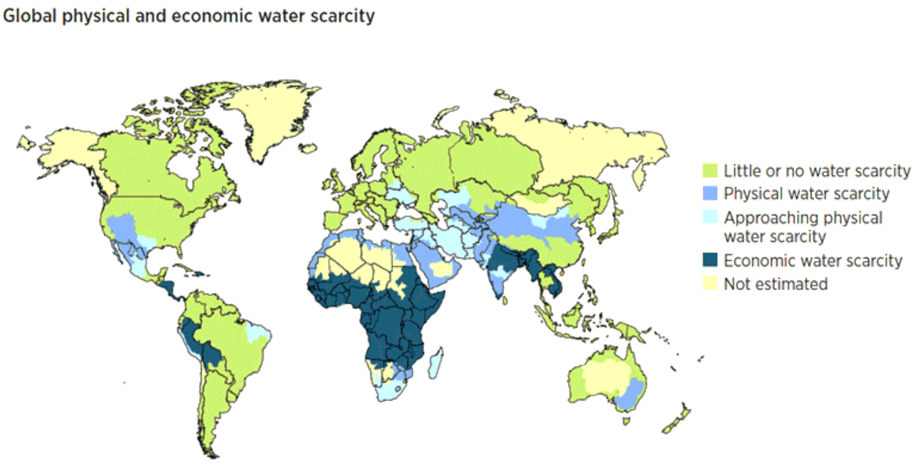

Figure 1: Areas of physical (there is not enough water to meet its demand) and economical (not enough technology to utilize existing water resources) water scarcity on a basin level in 2007 (Molden, 2007). Most of the regions categorized as 'water scarce' fall in semi- and arid tropics.

1.2.3 Food and Nutritional Insecurity in Semi- and Arid Tropics

Agriculture is the major livelihood activity for 70% of people residing in the semi- and arid regions (Graeub et al., 2015; Rockström, 2003). Food production is often inadequate to meet household food and nutrient requirements; hence people still have to buy food despite it being unaffordable (Molden, 2007). This may in part explain the high prevalence of food and nutritional insecurity. South Asia and sub-Saharan Africa are faced with the highest prevalence of malnutrition (under- and overnutrition) in the world (IFPRI, 2014). Undernutrition is commonly in the form of stunting (low height for age), wasting (low weight for age) and underweight in children under five years old (International Food Policy Research Institute, n.d.). It is estimated that one-half to two-thirds of stunted, wasted and underweight children reside in South Asia while one-third reside in sub-Saharan Africa (UNICEF et al., 2014). This implies that 80% to 90% of the world's undernourished children reside in the semi- and arid tropics. In addition, prevalence of micronutrient deficiencies is high with anemia (a condition caused by lack of iron) having the highest prevalence affecting at least 50% of women in the reproductive age (IFPRI, 2014). Conversely, being overweight and obesity affect at least 30% of the population (Wojcicki, 2014). These high levels of malnutrition are symptomatic of the poor dietary diversity in semi- and arid tropics. Based on these statistics, it is evident that nutrient intakes are not balanced (Mabhaudhi et al., 2016) to meet the requirements for a healthy life—food and nutritional security.

Food security was defined as a 'situation when all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (FAO, 1996). This definition was not properly translated into regional agricultural policies which led to a prioritization of food production over nutrition agendas. To emphasize the nutrition aspects and to clearly differentiate dietary quantity and quality, this review uses the term 'food and nutrition security' (Shetty, 2015; Thompson et al., undated). Agriculture, as the main source of food and livelihood in semi- and arid regions, provides an appropriate platform to tackle food and nutritional insecurity (Graeub et al., 2015; McDermott et al., 2015; Shetty, 2015). This can be achieved, in part, by increasing crop diversity and improving crop productivity which in turn strengthens the pillars of food and nutritional security. Furthermore, any such efforts should be defined and designed taking into consideration limitations posed by water scarcity i.e., recognizing the water-food-nutrition-health nexus (Mabhaudhi et al., 2016). This includes the promotion of crops that are adapted to dry areas and are nutrient dense (Mabhaudhi et al., 2016) such as legumes (Chivenge et al., 2015).

Previous food security initiatives in semi- and arid regions had a narrow focus of increasing production of cereals and root and tuber staple crops. Consequently, such staple crops currently occupy 70% of arable crop area. Although these staples have a role to play in providing daily energy requirements, they are often poor sources of other nutrients. This poses concerns on dietary diversity and could be partly why semi- and arid regions are faced with the burden of malnutrition. There is need for a balance between starch-rich foods and other nutrient dense foods in order to improve dietary diversity. According to Alleyne et al. (1977), one of the major concerns in diets of the rural poor is the issue of protein energy malnutrition. Legumes are a good source of protein and micronutrients and hence could be a good compliment to starchy diets (Abberton, 2010).

Khan (1987) reported daily per capita consumption of grain legumes to be 30 to 40 g in SSA and 40 to 60 g in SA. While in SA consumption is higher than in SSA, both regions are comparatively lower when compared to the world daily per capita consumption of 65 g. This is exacerbated by the fact that consumption of animal-based protein in both SSA and SA is also lower (20 g daily per capita consumption) compared to the world (34 g daily per capita consumption) (Singh and Singh, 1992). This highlights the poor protein diets in semi- and arid regions. Animal-based protein is expensive, hence there is more scope to increase protein in diets by increasing consumption levels of grain legumes.

1.3 Grain Legumes

1.3.1. Taxonomy

The word legume derives from the Latin word ‘legere’ which means ‘to gather’ (Hatcher and Battey, 2011). Legume refers to the fruit of plants that are usually gathered by hand. Legumes belong to the Fabaceae family and have an estimated 18,000 species in about 650 genera making them the third largest group of plant families after Orchidiacea and Compositae. The Fabaceae family comprises three sub-families Caesalpinioideae, Mimosoideae and Papilionoideae, depending on floral structure. The former two each comprise five tribes, which are mostly ornamental plants. The sub-family Papilionoideae comprises more than 32 tribes making it the biggest and most diverse sub-family; all grain legumes and major forage species belong to this sub-family. Of the 32 tribes, only seven tribes are edible (Allen and Allen, 1981) (Table 2); these form the focus of this review.

Table 2: Taxonomic affinities (tribe, subtribe, species and common names) of grain legumes.

Tribe	Sub-Tribe	Species	Common Name
Dalbergieae		*Arachis hypogaea* L.	groundnut
Cicerea		*Cicer arietum* L.	chickpea
Viciaea		*Lens culinaris* Med	lentil
		Pisum sativum L.	common pea
		Vicia faba L.	fababean
		Lathyrus sativus L.	grass pea
Genisteae	Lupininae	*Lupinus albus* L.	white lupine
		L lueus L.	yellow lupine
		L angustifolius L.	blue lupine
		L. mutabilis Sweet.	tarwi, chocho,
Phaseoleae	Erythrininae	*Mucana* spp. (velvet beans)	velvet beans
	Diocleinae	*Canavalia ensiformis* (L.) DC.	jackbean
		C. gladiata (Jacq.) DC.	swordbean
		Pachyrrhizus erosus (L.) Urban	yam bean
		P. tuberosis (Lam.) Spreng.	yam bean
		Calopogonium mucuniodes Desv	wild groundnut
	Glycininae	*Pueraria phaseoloides* (Roxb.) Benth.	puero, tropical kudzu
		Glycine max (L.) Merr.	soybean
	Clitoriinae	*Centrosema pubescens* Benth.	butterfly pea
		Clitoria ternatea L.	butterfly pea
	Phaseolinae	*Psophocarpus tetragonolobus* (L.) DC.	winged bean
		Lablab purpureus (L.) Sweet	lablab
		M. uniflorum (Lamb.) Verdc	horse gram, kulthi bean, hurali,
		Vigna aconitifolia (Jacq.) Marechal	moth bean
		V. angularis (Willd.)	azuki bean
		V. mungo (L.) Hepper	mung bean
		V. radiate (L.) Wilczek	mung bean
		V. subterranea (L.) Verdc.	bambara groundnut
		V. umbellate (Thunb.)	rice bean
		V. unguiculata (L.) Walp	cowpea
		Phaseolus acutifolus A.Gray	tepary bean
		P. coccineus L.	runner bean
		P. lunatis L.	lima bean
		P. polyanthus Greenm.	polyanthus bean
		P. vulgaris L.	common bean
	Cajaninae	*Cajanus cajan* (L.) Millsp.	pigeon pea
Indigoferae		*Cyamopsis tetragonoloba* (L.) Taubert	cluster-bean, siam-bean
Crotalariaea		*Crotalaria juncea* L.	indian hemp, sun hemp

1.3.2. Ecology

The highly diverse species of grain legumes are indigenous to various parts of the world. The ecology is, to a large extent, influenced by climate of its center of diversity (Allen and Allen, 1981; Smartt, 1990). The main centers of diversity are central America, South America, southwestern America, Africa and Europe. Owing to their wide diversity, grain legumes can be grown across different rainfall areas ranging from 200 mm to 1500 mm (Table 2). As such, some grain legumes are suited to the semi- and arid tropics that receive low annual rainfall. Although they grow well in environments similar to that of their center of diversity, they also adapt to other environments (Smartt, 1976) implying that they have wide adaptability.

Depending on species as well as season and cultivar, grain legumes take between 60 to 200 days to mature, making them suitable crops for sequential cropping (Table 2). Semi- and arid tropics are faced with uncertainties in rainfall distribution and occurrences as well as high frequency of dry spells which short season crops may be able to escape. Grain legumes are not associated with tolerance to water-logging and frost. This poor adaptability can be attributed to the centers of diversity being mild environments. Several grain legumes are short-day plants, an attribute owing to their centers of diversity, with a few exceptions such as white lupine, chickpea, lentil and common pea being long-day plants (Table 2). There are, however, bred short-day cultivars of white lupine, chickpea, lentil and common pea.

Average grain yield ranges from 300 to 14,000 $kg \cdot ha^{-1}$ depending on season, crop species, cultivar and management practices (Table 2). The low yield in some grain legumes, relative to cereals and root and tuber crops, has been suggested as a possible reason for their decline in rural cropping systems. However, grain legumes can offer other ecological benefits that cereal crops cannot.

One distinct ecological function that makes grain legumes unique is their ability to fix atmospheric nitrogen (Allen and Allen, 1981). While the Roman and Egyptian early settlers observed that in the presence of legume species soil was somewhat nutrient rich and plants were greener, it was only in 1888 when German scientists discovered that it was the legume root nodule that was responsible for this (Sur et al., 2010). Since then, this made grain legume crops of particular interest in faming systems, especially under marginal conditions (Crews and Peoples, 2004; Hutchinson, 1969; Zahran, 1999).

Table 2: Ecological characteristics (temperature, rainfall, growth cycle, photoperiod, soil type and yield) of selected grain legumes from the seven tribes of grain legumes.

Species	Min, Max Temp (°C)	Annual Rainfall (mm)	Growth Cycle (days)	*Photoperiod	Soil Type	Grain Yield (kg/ha)	Source
Dry bean	10, 30	600–650	70–200	Short day	Sandy loam to heavy clays	500–2500	(www.nda.agric.za, n.d.)
Groundnut	10, 30	500–600	125–150	Short day	Sandy loam	800–3500	(Smartt, 2012)
Chickpea	5, 25	400–600	84–125	Long day	Sandy to silt loam	630–850	(www.nda.agric.za, n.d.)
Soybean	10, 25	500–900	120–130	Short day	Clay loam	2000–4000	(Dugje et al., 2009)
Lablab	10, 35	700–1500	60–120	Short day	Deep sands to heavy clays	1000–2500	(Valenzuela and Smith, 2002)
Cowpea	8, 35	400–700	70–150	Short day	Sandy	1000–2000	
Bambara groundnut	10, 35	400–600	90–180	Short day	Sandy loam	300–3000	(Swanevelder, 1998)
Pigeon pea	–	–	100–200	Short day	Sandy to silt loam	718–1080	(Odeny et al., 2007)
Tepary bean	20, 48	200–600	60–120	Short day	Sandy loam	1410–2239	(Hamama and Bhardwaj, 2002)
Common Pea	5, 22	350–500	55–75	Day neutral	Sandy loam	1500–3120	(Boswell, 1926)
Faba bean	−2, 25	700–1200	110–130	Short day	Clay loam	2000–14,000	(Www.dpi.nsw.gov.au, n.d.)
White lupine	−7, 15	381–990	116–130	Long day	Sandy to silt loam	1570	(USDA, n.d.)

*Photoperiod: Short day = 10 h or less; Day neutral = 10 to 12 h; Long Day = 12 h or more.

1.3.3. Major vs. Minor Grain Legumes

There is a wide diversity of grain legume species and there are concerns that some species are more prominent compared to others in terms of breeding efforts, socioeconomic importance, area under cultivation and utilization. This dichotomy is often referred to in the literature as major and minor grain legumes. Other terms also used to refer to minor grain legumes are underutilized, neglected, orphan, promising and future grain legumes. There still lacks a consensus definition of underutilized, neglected or minor grain legumes. The lack of a consensus definition of major vs. minor legumes creates challenges when attempting to categorize legumes. Congenial examples would be of chickpea and cowpea where their underutilization is geographically distributed. Cowpea used to be widely used but now it is only common in African diets and its use is slowly diminishing in other areas.

In this review we define major grain legumes as those species that are recognized internationally regardless of their centers of diversity, occupy significant crop area, have been subject to formal crop improvement and research and have common and established value chains internationally. Minor grain legumes are those that are only of regional importance, are neglected or underutilized in any dimension (geographic, social and economic) and have no common international and established value chain.

1.4 Legume Value Chain

Approximately 30 grain legumes are grown in the semi- and arid tropics across different ecological niches. Chickpea, dry bean, groundnut, pigeon pea, cowpea and soybean account for more than 90% of grain legume production (Table 3). The remainder of the grain legumes (e.g., fababean, bambara groundnut, common pea and lablab, lentil) account for less than 10% of legume production (Abate et al., 2012). Singh and Singh (Singh and Singh, 2014) reported that in the last ten years there had been a significant upward trend (≈6%) in production of lentil in SA. Table 3 highlights the production trends of major and minor grain legumes where dry bean, groundnut and soybean are popular (each occupying > 5 million ha of land) across all regions and cowpea and chickpea are only popular in SSA and SA, respectively. In semi- and arid tropics more than 95% of grain legumes are produced under dryland conditions (Oweis, 1997). This implies that there is scope to increase grain legume production without increasing water withdrawals. This would be mostly through improvements in water productivity.

In semi- and arid tropics, legumes are planted on approximately 60 million hectares of land. This figure is minute when compared to starchy crops (cereals and root and tuber crops) that occupy over 250 million hectares in the same regions (Table 3). Starchy crops, as staple crops, have benefited from research related to their breeding, production, utilization and marketing. In this review, these components are referred to as a ‘research value chain.’ The ‘research value chain’ concept is used to describe the research activities and various stakeholders that products go through for them to be made available to consumers. The research value chain concept also extends to describe the value that products add to consumers and how they have been marketed and made available to consumers (Figure 2).

Starchy crops have established value chains and, owing to this high production, are widely available and utilized. If grain legumes are to be promoted, it is also imperative that research is carried out across the various points within a value chain. This review provides an overview of the grain legume research value chain to date. This will aid in identifying opportunities and constraints that exist for the promotion of grain legumes in rural farming systems of semi- and arid tropics.

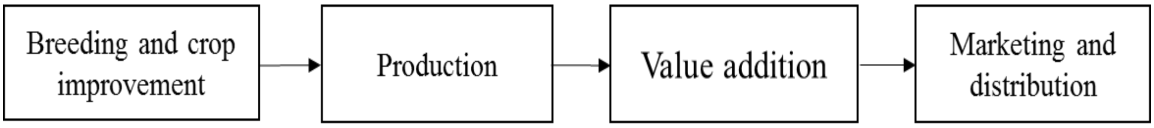

Figure 2: Research value chain from breeding and crop improvement to marketing and distribution.

Table 3: Production trends of selected grain legumes (chickpea, dry bean, groundnut, pigeon pea, soybean and cowpea) in the world and semi- and arid tropics (sub-Saharan Africa, and South Asia) for the period 2010–2012 (Adapted from Abate et al. (2012) and Nedumaran et al. (2015) with some minor modifications from faostat.fao.org).

	Area (1000 ha)	**Yield (kg·ha^{-1})**	**Production (1000 Metric Ton)**	**% of World Production**
		World		
Chickpea	10,914	818	8929	-
Dry bean	27,232	723	19,705	-
Cowpea	14,500	454	6155	-
Groundnut	22,633	1607	36,379	-
Pigeon Pea	4655	885	3463	-
Soybean	92,622	2348	217,397	-
Lentil	3571	1904	2900	-
		Sub-Saharan Africa		
Chickpea	398	769	315	3.5
Dry bean	5190	596	3045	16
Cowpea	11,440	450	5145	84
Groundnut	9057	1007	8942	40
Pigeon Pea	499	729	363	10
Soybean	1228	1060	1279	1.3
Lentil	100	1094	90	2
		South Asia		
Chickpea	8334	855	6792	76
Dry bean	11,532	985	5908	30
Cowpea	159	975	154	3
Groundnut	7038	1122	8457	31
Pigeon Pea	4118	840	3068	88
Soybean	8490	1275	5735	9.2
Lentil	1700	633	1088	33

1.4.1. Breeding and Crop Improvement

Progress in breeding and crop improvement has been relatively slow, especially when compared to cereals such as maize, rice and wheat. Since the 1970s, grain legume breeding focused on disease resistance, growth habit and duration in relation to increasing yields (Oppen, 1981). It was only post-2000 that characteristics such as drought and heat-stress tolerance and environmental adaptability (genotype × environment) became topical (Duc et al., 2015; Sharma et al., 2013). Recently, pre-breeding of some minor grain legumes indigenous to semi- and arid tropics (e.g., cowpea, pigeon pea, and chickpea) has come into light for their adaptation to drought and heat stress.

Consultative Group on International Agricultural Research (CGIAR) institutes such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), International Institute of Tropical Agriculture (IITA), and the Centre for Agricultural Research in Dry Areas

(ICARDA) have largely driven breeding and crop improvement of grain legumes for the semi- and arid tropics. This is with the exception of soybean breeding and crop improvement that has also been driven by private seed companies. Consultative Group on International Agricultural Research institutes are also responsible for germplasm conservation with ICRISAT and IITA maintaining the highest number of grain legume accessions. ICRISAT maintains 14,968 accessions of groundnut, 13,771 of pigeon pea and 81,000 of chickpea (www.icrisat.org) while IITA maintains 15,115 accessions of cowpea, 1, 742 of soybean, 1,815 of bambara groundnut and ≈ 2,000 of other minor grain legumes combined (www.iita.org). It is interesting to note that despite the large germplasm collections, < 1% has so far been utilized in breeding programs (www.icrisat.org). This highlights low utilization of genetic resources by breeders. According to Foyer et al. (2016), the low utilization of genetic resources has led to stagnation of grain legume yields. In order to increase adoption of grain legumes, improved varieties that are drought- and heat-stress tolerant, nutrient dense and high yielding should be made available. This is still in its infancy and there is need for novel biotechnological techniques such as marker-assisted selection to speed up grain legume improvement. This should include whole-genome sequencing in the existing legume accessions including crop wild relatives to develop new molecular markers.

1.4.1.1 Seed Systems

In semi- and arid tropics, 80 – 90% of grain legume seed systems are farmer-driven (farmer seed systems). This means that farmers use farm-saved seed from the previous harvest, acquire them from other farmers through barter or gifts or obtain them from informal local markets (Almekinders et al., 1994; Almekinders and Louwaars, 2002; Bèye and Wopereis, 2014; Coomes et al., 2015; Jones et al., 2001; Reddy et al., 2010; USAID, 2012; Wekundah, 2012). This seed is often in the form of landraces, which are open-pollinated varieties that are often the product of many years (>100 years) of natural and farmer selection (Zeven, 1998). In some instances, seed companies supply landraces of both major and minor grain legumes that are not certified or tested (Almekinders and Louwaars, 2002; Reddy et al., 2010; Wekundah, 2012). They take advantage of their strategic positioning in the agriculture sector to source seed of grain legumes and supply them to research institutions or farmers. Farmers have also been reported to purchase hybrid seed, which is the product (first-generation progeny) of a cross between two unrelated (genetic dissimilar) parents (Mathews and Saxena, 2005), and then recycle it similarly to how they recycle landraces (Reddy et al., 2010; Wekundah, 2012). However, unlike for landraces and other open-pollinated varieties, recycling hybrid seeds has negative implications on subsequent seed quality. In addition, most grain legumes that are grown in the semi- and arid tropics are self-pollinating plants, hence recycling seeds may result in loss of vigor, decrease in immunity to diseases and reduced adaptability to changing environments (Wekundah, 2012).

Adoption of improved seed will significantly increase productivity assuming that it is accompanied by the adoption of best management practices. Promoting hybrid seed may also come with increased dependency on other agricultural inputs such as chemicals, fertilizers and water (Bezner Kerr, 2013; Kerr, 2012). This may create new challenges under low input agriculture systems that typify the semi- and arid tropics as farmers may not be able to afford the use of external inputs. In this regard, the use of improved open-pollinated varieties adapted to a range of environments would be more desirable. Thus, promoting grain legumes in cropping systems will require formulation of dynamic strategies that ensure availability and farmers' adoption of improved seed as well as adoption of best management practices that allow for yield maximization. This should be underpinned by viable and sustainable seed systems (formal and informal) that are beneficial to all role players (breeders, government and farmers).

Formal seed systems are discouraged by farmers' tendency to recycle seed, thereby decreasing the demand for certified seed (Muigai et al. undated). However, farmers' tendency to recycle seeds is influenced by several factors such as high cost of purchasing hybrid seed every season and lack of formal seed suppliers in rural areas. In addition, use of hybrids also risks loss of benefits such as ease of exchanging or sharing seed as well as earning income from selling seeds on the informal market. This highlights the need to integrate formal and informal seed systems when promoting grain legumes. Muigai et al. (undated) suggested integrating informal seed channels into formal seed structures by providing foundation seed to selected rural farmer groups to multiply. This should be supported by extension advice on seed production, processing, treatment, storage and developing a legal framework that permits marketing of certified and uncertified seed of acceptable genetic purity and germination quality. This will provide resource-poor farmers with quality seeds of improved varieties at affordable prices. A similar strategy is underway in Nigeria aimed to "sustainably improve farmers' access to high quality and affordable cassava planting material through the development and promotion of models for seed provisions" (www.iita.org). Such models, if successful, could be adopted and restructured for grain legumes.

1.4.2. Production

1.4.2.1. Agronomy

Soil fertility is one of the major constraints in subsistence agriculture. Studies have shown that including grain legumes in cropping systems improves soil fertility (Karpenstein-Machan and Stuelpnagel, 2000; Reckling et al., 2015; Smith et al., 2016). This could be through relay cropping, intercropping, crop rotations or double cropping (Karpenstein-Machan and Stuelpnagel, 2000; Reckling et al., 2015; Smith et al., 2016). Legumes have also been successfully used as cover crops to improve soil fertility, control pests and suppress weeds (Blevins et al., 1990; Chabi-Olaye et al., 2005; Rühlemann and Schmidtke, 2015). While the role of grain legumes in increasing soil nitrogen cannot be denied, other macro- and micro-nutrients cannot be ignored. A deficiency of other nutrients such as phosphorous, boron and molybdenum may hinder nitrogen fixation (Divito and Sadras, 2014; Sur et al., 2010; Zahran, 1999). In addition, subsistence farmers often do not use inoculants to stimulate the formation of nitrogen-fixing nodules. Studies on dry bean, groundnut, soybean and cowpea have shown that under marginal soils inoculating seed with Rhizobia improves nitrogen-fixation capacity and yield (Cheruiyot et al., 2013; Mweetwa et al., 2014). There should always be a balance of the essential soil nutrients that are required for growth and reproduction of grain legumes to get the maximum yield. Rural farmers should have access to soil analyses. This will aid in correcting soil fertility to maximize yield. While use of fertilizer may be limited due to affordability, options such as manure, compost and crop residues could be explored.

Another major agronomic component of grain legumes is weeding. According to Avola et al. (Avola et al., 2008), grain legumes are poor competitors with weeds. Without proper weed control, weeds can cause significant yield losses (Olorunmaiye, 2010; Rubiales and Fernández-Aparicio, 2011). Groundnut, soybean and bambara groundnut have been observed to be among the poorest competitors with weeds and require constant weeding compared to other legumes such as cowpea and pigeon pea (Abdelhamid and El-Metwally, 2008; Bhale et al., 2012; Martin et al., 2009; Mhango et al., 2013). A study in Malawi showed that one of the factors influencing farmers' adoption of grain legumes in cropping systems was the high labor required due to constant weeding (Mhango et al., 2013). There is need for sustainable weed control strategies for poor rural farmers to increase adoption of grain legumes. This should include low-cost mechanical weeding machines and agronomic practices to reduce weed infestation. The latter includes research on the effects of mulching, spatial arrangements and critical periods for weed control in different grain legume species.

The adverse environmental conditions that typify most of the semi- and arid tropics suggest that currently grain legumes are being grown under sub-optimal conditions. This could explain the high incidences of aflatoxins reported in legumes, especially groundnut. Aflatoxins are a group of chemically similar toxic fungal metabolites (mycotoxins) produced by certain moulds of the genus *Aspergillus* growing on a number of raw food commodities (Luchese and Harrigan, 1993). Aflatoxins, notably *Aspergillus flavus*, are naturally abundant and often found when certain grain legumes are grown under stressful conditions such as drought (Heathcote and Hibbert, 1978). Aflatoxin levels are high in groundnut (up to 11,865 µg/kg) (Chala et al., 2013). This has become a concern for the production and export of groundnuts in semi- and arid tropics (Www.tradeforum.org, n.d.). This is disconcerting; for the period 2000–2006, ≈80% of SSA's groundnut exports to the European Union were non-compliant with the Codex standard of aflatoxin levels (>50 ppb) (Diaz Rios, 2008). Loss of markets therefore becomes a disincentive for farmers to continue production. Improved agronomic practices could lower the incidence of aflatoxins.

With the exception of major grain legumes, there is a lack of robust empirical information describing the agronomy of most grain legumes suitable for cultivation in the semi- and arid tropics. While this information may be available in few national agricultural research stations, it remains inaccessible to farmers. Rural farmers who still cultivate minor grain legumes mostly rely on indigenous knowledge and continue to get low yields, further marginalizing the continued production of minor grain legumes.

1.4.2.2. Water Use and Water Use Efficiency

In semi- and arid tropics, where water is the most limiting input to crop production, crop water requirement is an important factor. Crops that use less water are becoming increasingly important as one of the strategies to increase food production under conditions of water scarcity. Research on water use of grain legumes showed that cowpea and fababean had low water use ranging between 78 and 258 mm and 101 and 261 mm, respectively (Table 4). Lentils could also be considered low water users, especially when compared to major grain legumes such as dry bean, groundnut and soybean that had water use ranging from 318 to 463 mm, 697 to 809 mm and 598 to 690 mm, respectively (Table 4). The high water requirement of groundnuts could also explain the high incidence of aflatoxins as they are more prone to water-deficit stress. It could thus be inferred that cowpea, fababean, lentil, chickpea and common pea are suitable for growing in arid and semi-arid conditions where seasonal rainfall is low (200 to 400 mm) (Table 4).

However, low water use does not necessarily imply high water use efficiency (WUE). Water use efficiency of legumes ranges from 1.7 to 15.9 $kg \cdot ha^{-1} \cdot mm^{-1}$ with various species showing noticeable differences in WUE (Table 4). These values are low when compared to WUE values reported for cereal and root and tuber crops. For maize and sorghum, the lowest reported WUE value was 4 kg·ha^{-1}·mm^{-1} (Igbadun et al., 2006) while the highest was up to 85 kg·ha^{-1}·mm^{-1} (Saeed and El-Nadi, 1998; Tijani et al., 2008). Potatoes on the other hand have WUE values as high as 195 kg·ha^{-1}·mm^{-1} (Badr et al., 2012). It cannot be disputed that cereals and root and tuber crops are more water use efficient when compared to grain legumes. Values of water use and WUE are, however, wide-ranging and lack robustness as they were determined under different management and environmental conditions and are thus not conservative (van Halsema and Vincent, 2012). Water productivity (WP), which is the net benefits accrued per unit water consumed (Molden et al., 2003), offers greater spatial and temporal stability and is a true efficacy parameter of the crop production process (van Halsema and Vincent, 2012).

Table 4: Water use and water use efficiency (WUE) of selected grain legumes.

Species	**Water Use**	**Yield**	**WUE**	**Climate**	**Source**
	mm	**kg·ha^{-1}**	**kg dry matter ha^{-1} mm^{-1}**		
Dry bean	318–463	1407–4031	1.7–10.9	Mediterranean	(Muñoz-Perea et al., 2007)
Groundnut	697–809	2080–4240	3.96–5.25	Semi-arid	(Patel et al., 2008)
Chickpea	150–340	358–1357	1.9–3.6	Mediterranean	(Zhang et al., 2000)
Soybean	598–690	710–1910	1.16–2.80	Semi-arid	(Obalum et al., 2011)
Cowpea	78–258	1020–1340	0.11–0.2	Semi-arid	(Abayomi et al., 2008)
Bambara groundnut	300–638	500–2400	0.1–0.12	Semi-arid	(Mabhaudhi et al., 2013)
Pigeon pea	331–551	1816–2643	3.38–6.97	Semi-arid	(Vimalendran and Latha, 2014)
Common pea	177–266	1040–2240	6–15.9	Mediterranean	(Siddique et al., 2001)
Fababean	101–261	420–1920	1.7–12.5	Mediterranean	(Siddique et al., 2001)
Lentil	160–308	339–1657	2.3–4.5	Mediterranean	(Zhang et al., 2000)
White lupine	178–272	1570	2.1–8.5	Mediterranean	(Siddique et al., 2001)

NB. Data were obtained from experiments conducted under varying environmental and management conditions.

1.4.3. Post-Harvest Handling, Storage and Value Addition

After harvesting, products go through some sort of transformation from their original state to a more valuable state. This is referred to as value addition. Value addition can be viewed as the benefits obtained from a product with respect to quality, form and functionality (Anderson and Hanselka, 2009). This includes the transformation of food to nutrients that are utilized by the body (Boland, 2009). Value addition also includes agro-processing which describes the manufacturing processes involved to derive products from agricultural raw products (FAO, 1997).

1.4.3.1. Post-Harvest Handling and Storage

Subsistence farmers still harvest grain legumes manually. This can lead to splitting and significant yield losses (≈20%) (Williams, 1994). In many parts of India, low-cost mechanical harvesting equipment has been designed for groundnut and dry bean to minimize labor and grain losses during harvesting (Mothander et al., 1989). There is also a need for similar low-cost technologies for other grain legumes coupled with suitable and appropriate maturity and harvest indices to aid farmers in correctly determining time of harvest; this will minimize grain losses during harvesting.

One of the major advantages of grain legumes is their long shelf life hence availability throughout the year. However, this is largely determined by storage conditions. Once the grain legumes have been threshed, the seeds must be stored at ≈12% moisture content and temperatures below 15 °C to avoid discoloration, mould and fungi. Some grain legumes are very sensitive during storage and, if care is not taken, up to 50% of storage losses can be incurred (Kat et al., 1992). For example, when chickpea seed is harvested, its outside seed coat usually has a lower moisture level than the inside of the seed. If left to sit in storage, the moisture level can balance out (tempering/sweating), causing the overall moisture level to rise. In this way, chickpeas that are harvested at a safe moisture level can, after a week, exceed the recommended 14%. Left untreated, the harvest can spoil. For this reason, chickpea producers often store the crop in a hopper-bottomed bin that has aeration, which can help bring down the moisture level (www.pea-lentil.com, n.d.). This information may not be available to subsistence farmers and they may not have access to specialized storage containers. This is one of the reasons why there is a shift towards promoting value chain research; if chickpeas are promoted to farmers, this has to be accompanied by knowledge of chickpea post-harvest handling and storage as well as provision of specialized storage containers to avoid detrimental post-harvest losses.

Under proper storage conditions, grain legumes can be stored for up to three years (Summerfield, 2012). Considering the predicted increase in drought occurrences, this is an important attribute as stored grain can be consumed during drought and when there is a shortage of food. However, weevils, rats, bruchids and other storage pests can be a problem in storage and proper chemicals need to be used to control them (Summerfield, 2012). Poor storage environment can result in color loss, moisture absorption, and desorption as well as hardness or case hardness issues (McCormack, 2004). In semi- and arid tropics, such storage challenges are frequently experienced by subsistence farmers and this could be partly why they are discouraged from producing large quantities. If there are no markets to sell the surplus grain to, this acts as a further disincentive to farmers and they subsequently only produce grain they can consume in the short term. Poor storage conditions may also have an effect on the seed quality (viability and vigor) reserved for the next season. While grain legumes may have a longer shelf life compared to vegetables, dairy products, fruits, and meat products, currently this advantage has not been fully explored due to farmers’ lack of appropriate storage conditions. This ultimately compromises the potential of grain legume availability all year round.

1.4.3.2. Nutritional Quality

Grain legumes contain 5% to 39% protein with white lupine and soybean being the highest protein sources (Table 5) (Messina, 1999; Večerek et al., 2008). By comparison, vegetables and cereals contain 2% and 8% to 12% protein, respectively (www.pea-lentil.com). This makes grain legumes the best source of proteins among all the food crops. In the absence of meat, grain legumes offer the best protein supplement to meet the recommended daily allowance (RDA) of 56 g (Table 5). Soybean contains the most protein compared to other grain legumes; this could explain why it has been widely accepted. In addition to being good sources of protein, some grain legumes such as bambara groundnut, soybean and cowpea contain reasonable amounts of carbohydrates (up to 56%) (Table 5). Dry bean and lablab have low carbohydrate content (< 10%), compared to the other grain legumes and the reason for this is not well understood.Soybean and tepary bean contain sufficient iron to meet the RDA for an adult male and almost enough to meet the RDA of an adult female (Table 5). This implies that incorporating these crops in diets could alleviate the high prevalence of anemia in semi- and arid tropics. Soybean, dry beans, bambara groundnut and tepary bean contain >160 mg of calcium which is higher than the same serving of milk (125 mg per 100 g milk) (Table 5) (Smith et al., 1985).

Cereals are the major source of carbohydrates but are poor sources of proteins and micronutrients providing ≈12 g protein, 10 to 140 mg calcium, 0.5 to 3.9 mg iron, and 0.6 to 3.3 mg zinc per 100 g serving (McKevith, 2004). This is comparatively lower than grain legumes and justifies the need to promote grain legumes to compliment cereals in diets. However, these values are for raw seeds and it will be impetuous to not consider how nutritional value is affected by the different processes that the grain legumes go through before they are consumed. The presence of anti-nutritional factors (ANFs) and aflatoxins should also be considered as they pose an impediment to utilization of grain legumes.

Table 5: Average nutrient content of selected grain legumes per 100 g raw mature seeds.

Species	Energy	Protein	Carbohydrates	Fat	Vit A	Iron	Zinc	Calcium	Source
	Kcal		g		µg		mg		
*RDA		56.0; 46.0	130.0	20.0–35.0	900.0; 700.0	8.0; 18.0	11; 8	1000.0	(Joint and Organization, 2005)
Dry bean	333.0	21.8	2.5	2.5	–	4.7	–	183.0	(Geil and Anderson, 1994)
Groundnut	570.0	25.0	21.0	48.0	–	2.0	3.3	62.0	(Atasie et al., 2009)
Chickpea	164.0	8.9	27.0	2.6	1.0	2.89	1.5	49.0	(Iqbal et al., 2006)
Soybean	446.0	36.5	30.2	19.9	1.0	15.7	4.9	277.0	(Liu, 1997)
Lablab	50.0	2.9	9.2	0.3	–	0.76	0.4	41.0	(Deka and Sarkar, 1990)
Cowpea	116.0	7.8	20.8	0.5	–	2.51	1.3	24.0	
Bambara groundnut	367.0	20.6	56.0	6.6	–	5.96	7.9	219.0	(Yao et al., 2015)
Pigeon pea	136.0	7.2	28.9	1.6	–	1.6	1.0	42.0	(Singh et al., 1984)
Tepary bean	–	–	–	–	–	12.6	5.0	165.0	(Sheerens et al., 1983)
Common pea	81.0	5.4	14.0	0.4	38.0	1.47	1.2	25.0	
Fababean	341.0	8.0	18.0	0.7	–	6.7	3.1	103.0	(Crépon et al., 2010)
Lentil	353.0	26.0	60.0	1.0	–	7.54	4.8	56.0	
White lupine	1741.0	39	11.5	5.8	–	3.1	4.5	0.68	(Večerek et al., 2008)

*RDA = Recommended Dietary Allowance (Male; Female); Nutritional values may vary from one variety to the other.

1.4.3.2.1 Anti-Nutrient Factors

Anti-nutrient factors (ANFs) are chemical compounds synthesized by plants for their own defense. Metabolically, synthesis of anti-nutrients is a favorable attribute as it is an adaptive mechanism. However, synthesis of anti-nutrients is through inactivation of some nutrients that are important to humans (Gemede and Ratta, 2014). This ultimately decreases nutritive value of foods. Common ANFs in legumes include tannins, phytates, oxalates, saponins, lectins, alkaloids, protease inhibitors cynogenic glucosides and oligosaccharides. They occur in small quantities ranging from 0.2% to 4%. Some ANFs cause undesirable effects to humans when consumed in excess (Gilani et al., 2012). Phytic acid impairs the absorption of iron, zinc and calcium. Lectins are difficult to digest and may affect the cells lining the intestinal tract. Saponins increase intestinal permeability also known as leaky gut (Messina, 1999). Oligosaccharides occur in large quantities (≈ 20–50 mg/g) and are responsible for the flatulence associated with consuming legumes (Messina, 1999). However, ANFs are not all undesirable; they have some benefits. For example, phytates and saponins are believed to lower the risk of colon and breast cancer (Bennink, 2002). Despite the latter, generally anti-nutrients are not desirable. Minimizing ANFs in grain legumes is linked to improving agronomic practices and minimizing stress during production.

1.4.3.3. Processing and Utilization

In rural communities, the processing and utilization of grain legumes has a long history that is intimately linked to women and their traditional livelihood tasks (Ezumah and Di Domenico, 1995; Modi et al., 2006). This will be an advantage for promoting grain legumes for improved household nutrition in semi- and arid tropics where women have greater influence over household food choices, child nutrition and ultimately health (FAO, 2015). Grain legumes can play an increasingly important role as a source of income in rural communities, especially those near towns and cities. The money could be used towards other household needs and children’s education (FAO, 2015).

Depending on the type of grain legume and the intended use, the various processes may differ. One of the initial steps (primary processes) is to further dry the harvested pods. Drying is done under the sun and, depending on resources, grains are spread on the ground or on a raised platform. After sun drying comes two processes that are considered time consuming and laborious when done manually. This includes (i) dehusking which is the process of removing the husks; and (ii) winnowing which involves separating the husks from the seed (Subuola et al., 2012). Resource-poor farmers use manual methods (mortar with pestles and wooden or stone shellers). These processes require manual labor and this could also partly explain the low cultivated areas for grain legumes in rural households. Labor is limited due to rural to urban migration of the economically active age group (Haan, 1997). In this regard, the development of low-cost technologies for processing the harvest could go some way in encouraging farmers to allocate more land to grain legumes.

Secondary processes include, but are not limited to, soaking, cooking, fermenting and germinating (Subuola et al., 2012). Cooking improves appeal, nutrition and digestibility of grain legumes. In several grain legumes, cooking time (boiling) of pods and/or grains is comparatively lengthy (three to five hours). This could be a disincentive in rural areas where fuelwood and water for cooking are scarce (Deshpande, 2000). Soaking and cooking time of grain legumes have also been shown to affect nutritional quality of some grain legumes (Güzel and Sayar, 2012). It was observed that proteins, minerals and carbohydrate content in seeds decreased by 16% to 20%, 30% and 18% to 40%, respectively, following cooking (Mahadevamma and Tharanathan, 2004; Meiners et al., 1976; Siddhuraju et al., 2000). This raises the challenge of developing appropriate cooking methods that maximize nutrient retention. Although the challenges related to cooking time and nutrient retention have been raised, research still lags in providing solutions. Such solutions could be useful in unlocking their value.

While legumes have mainly been considered for their grains, young tender leaves and flowers of some grain legumes can also be consumed as vegetables (Manay and Swamy, 2001; Toensmeier, 2007). Leaves and flowers are rich in vitamins and minerals (Manay and Swamy, 2001; Toensmeier, 2007). Tapping into this potential could contribute to dietary diversity through unlocking a useful source of vitamins and minerals. This could be explored when other leafy vegetables are not available as well as to increase the leafy vegetable basket. However, there are scant studies reporting on the nutritional status of young tender leaves and flowers of legumes as well as harvest times.

1.4.3.3.1 Animal Feed

In addition to human consumption, grain legumes can be used for fodder. The value of grain legumes in livestock production has been explored for forage legumes such as *Medicago sativa* (alfafa), clover (*Trifolium* spp.) and vetch *(Vicia sativa*). This is mainly targeted for commercial livestock production and is unaffordable for subsistence farmers. Subsistence farmers can utilize grain legume residues for fodder but this remains underutilized and poorly documented in the semi- and arid tropics (Sumberg, 2002). After harvesting pods, leaves of grain legumes such as chickpea, lentil, cowpea, common pea, soybean, fababean and lablab can be left in the field for animal grazing. Grain, leaves and husks of soybean, common pea, fababean, lupine, cowpea, bambara groundnut, velvet bean, chickpea, lentils and lablab can be ground and used as animal feed (Crépon et al., 2010; Dixon and Hosking, 1992; Huisman and Van der Poel, 1994; Jezierny et al., 2010). They form an important plant-based protein source that can be fed directly or mixed with cereals to form complete meals (Nji et al., 2004; Siddhuraju et al., 2000). The fact that most grain legumes have a dual purpose (i.e., human and animal feed) makes them ideal for inclusion in crop–livestock systems that characterize smallholder and subsistence agriculture.

1.4.3.3.2 Agro-Processing

Agro-processing enables conversion of farm produce to various commodities that can attract different markets. Agro-processing increases shelf life, reduces wastage and has the potential to increase income of subsistence farmers (Food and Agriculture Organization, 1997). Due to rising incomes and change in lifestyles, the demand for processed foods is increasing, creating opportunities for the agro-processing industry (International Monetary Fund, 2014; Timmer, 1995).

Agro-processing in various countries has been biased towards cereals, fruits, vegetables, oil, textiles and beverages. In semi- and arid tropics, grain legume agro-processing is dominated by the major grain legumes. Dry beans are commonly tinned or are sold raw with proper packaging and branding. Groundnuts are commonly sold roasted with proper packaging and branding or are processed into peanut butter. Soybean is the most versatile among all the grain legumes and can be processed to milk, curd, sauce, cheese and chunks. These products are common amongst vegetarians and those who are allergic to cow milk. In addition to the above products, groundnuts and soybean are processed to produce oil. The multiple uses make soybean and groundnut the most economically important grain legumes.

On the contrary, minor grain legumes have received less attention in terms of agro-processing. This inadvertently reduces their utilization and subsequent demand; this may explain why seed companies tend to not focus on them. Despite the lack of research, several minor grain legumes have potential for processing into various products. For example, bambara groundnut seed can be used to produce vegetable milk although this potential is currently underexplored (Agunbiade et al., 2011; Brough et al., 1993). India has made a significant milestone on agro-processing of minor grain legumes (chickpeas and lentils). Promoting agro-processing of minor grain legumes could open up new value chains and opportunities for rural farmers to participate in these value chains. Agro-processing would also increase demand for minor grain legumes thus necessitating increased production and availability of seed. Increasing opportunities for rural farmers to earn incomes and exit poverty is key to sustainable development in the semi- and arid tropics.

In Thailand, agro-processing reduced poverty in rural areas through (i) the purchase of agricultural products by the agro-processing industry; and (ii) establishing agro-processing industries near rural areas in-order to employ poor farmers (Watanabe et al., 2009). This provides a successful case study for governments in developing countries to establish grain legume agro-processing facilities for rural farmers. India, in its efforts to encourage grain legume production, made available more than 10,000 small-scale grain legume mills (Chengappa, 2004). Though this is incomparable to cereal hullers and mills (>200,000), it served as a starting point (Chengappa, 2004). Developing countries should embark on similar projects to facilitate agro-processing in rural areas and make grain legume products more available at low cost. To realize this, research, development and innovation should support the development of acceptable standards, branding and marketing. Promotion of agro-processing could create business opportunities for rural farmers (Singh et al., 2007).

1.4.4. Marketing

Ultimately, within the value chain, there must be a market to consume the grain legume products. Marketing structures are divided into three levels—(i) the traditional/local market; (ii) wholesaler/processor market; and (iii) the retailer market. For grain legumes in the rural areas of semi- and arid tropics, the traditional market is the dominant market level. Major grain legumes are available on both the traditional and retail market while minor grain legumes are only found on the traditional market (Giller et al., 2011). On the traditional market, grain legumes are sold whole with minimum value addition. As a result, they do not fetch a high price and products move slowly due to limited utilization. This discourages farmers from producing surplus grain legumes hence resorting to growing cereals. Cereals have a higher demand on all market levels hence they sell fast. This makes it attractive for subsistence farmers as they are guaranteed to sell their product.

Cereals have also enjoyed much innovation with regards to their agro-processing. There is a wide variety of cereal products thus attracting a wider market and ultimately increasing utilization. The number of grain legume products are only one-third of the number of cereal products (Kachru, 2010). This is further evidence that cereals are more utilized than grain legumes. To increase grain legume utilization, the same strategy of product diversification could be employed. This will broaden the grain legume market and ultimately increase utilization. However, product diversification is highly dependent on agro-processing. Currently, agro-processing has only focused on a few major grain legumes. Effective product diversification will require inclusion of minor grain legumes. Minor grain legumes are currently being manually processed by farmers in rural areas implying that there is scope for agro-processing in these grain legumes. There is need for investments in research, development and innovation in order to establish successful and sustainable large- and small-scale grain legume agro-processing facilities. However, such development should pay attention not to exclude rural farmers.

Rural farmers are the primary producers of grain legumes. The majority of them continue to live in poverty and are the most vulnerable to food and nutrition insecurity (FAO, 2015). The current marketing and distribution channels for value-added grain legumes have not benefitted rural farmers. Value added products are expensive in retail stores and the traditional market offers limited utilization. Thus, promotion of grain legume agro-processing as a strategy to market grain legumes should include rural farmers as they are the main target of strategies to alleviate food and nutrition security. This will benefit rural farmers through (i) product diversification which will ultimately increase utilization and subsequently improve protein intake in households; and (ii) provide value added products that will attract a wider market and that will sell faster, thereby translating to increased household income.

1.4.5. Grain Legumes: Opportunities and Constraints

The grain legume research value chain has largely focused on grain legumes of regional economic importance. With approximately 30 grain legume species being grown in the semi- and arid tropics, only less than 50% of these have received significant research attention. This is mainly because research funding has favored a few major grain legumes (chickpea, dry bean, cowpea, fababean, groundnut, lentil, pigeon pea and soybean). These grain legumes are also part of the CGIAR’s mandate crops, hence they have received significant research attention compared to other minor grain legumes (Gepts et al., 2005; ICRISAT et al., 2012). There is an opportunity to increase the grain legume basket by tapping into the potential of other minor grain legumes. Thus far, there is scant documented information on these crops due to lack of funding to support research, development and innovation on these crops.

Breeding and crop improvement of grain legumes has been limited by the poor demand of seed. In semi- and arid tropics, farmers continue to recycle their own seed. Failure by breeders to improve farmers’ varieties and tap into certain beneficial traits has confined the production of minor grain legumes to the ecological niches where they have been conserved. The semi- and arid tropics are rich in grain legume biodiversity which is currently underutilized. With increased promotion of grain legumes there is an opportunity to exploit these genetic resources. This could result in development of high-yielding cultivars that are suitable for growing in water scarce environments. The reported low yields of grain legumes have made them unattractive for farming. The low yields could also be as a result of lack of improved cultivars and farmers' agronomic knowledge which is mostly based on indigenous knowledge.

Soil fertility is one of the major challenges in rural cropping systems (Sanchez, 2002). Grain legumes fix nitrogen, a unique feature that makes them important under marginal conditions. While nitrogen fixation is a key point for the promotion of grain legumes, there is poor understanding that nitrogen fixation is influenced by other factors such as presence of nitrogen fixing bacteria, lack of other soil nutrients and abiotic stresses (Carranca et al., 1999; Zahran, 1999). Also, as previously alluded to, nitrogen fixation is often limited by the lack of inoculants in rural cropping systems. Water is the most limiting resource in agriculture; this has led to crop failures, poor yields, and high levels of aflatoxins and ANFs in major grain legumes. Several minor grain legumes are more drought tolerant and water use efficient than major grain legumes and offer opportunities for cultivation in dry areas where water is most limited. This would imply that their ability to fix nitrogen would be less sensitive to water stress as well; however, there is a need to test such a hypothesis. In this regard, they also offer opportunities for addressing food and nutrition insecurity in marginal agricultural production areas where most major crops may fail.

Grain legumes are nutritious and have the potential to improve nutritional status of the rural poor. However, most published nutrition values are derived from raw seeds. There is need for research that assesses the nutritional profile of grain legumes after processing as this would be more informative to dietary intake. Most grain legumes are characterized by long cooking time and are processed differently by cultures of semi- and arid tropics. Long cooking time often creates challenges as it means more water and energy are required to prepare them—resources that are equally scarce in rural areas. This suggests that there are opportunities for breeders, agronomists and nutritionists to work together to unlock such challenges. This would lead to improved utilization of grain legumes.

Owing to their long shelf life, legumes are available throughout the year thus offering a more sustainable protein source for poor rural farmers. However, even with this characteristic, given the reported challenges with post-harvest handling and storage, grain legumes are not reaching their potential shelf life. There are opportunities for agricultural engineers to develop low-cost post-harvest technologies for use in rural areas. Improving storage could serve as incentive for farmers to produce more of a crop as they know they can store it for longer periods.

The market for grain legumes, in particular minor grain legumes, remains underdeveloped. This confines their utilization to the niche areas in which they are produced. Consequently, grain legumes have become a poor and slow income-generating source for rural farmers, acting as a disincentive to their continued production despite the benefits associated with them. Opportunities that exist in agro-processing could lead to the opening of new markets through value addition and product diversification. Improved income realized from agro-processing could promote autonomous pathways out of poverty for poor rural households.

1.5. Recommendations

There is a large diversity of grain legumes that fit into various agro-ecologies. This implies that grain legumes can be grown in various environments. Focusing on a few specific grain legumes leaves farmers with limited choices and forces farmers to grow them in unsuitable environments and risk crop failure. If grain legumes are to be promoted to increase dietary diversity, then there is need to broaden the grain legume basket by increasing research, development and innovation on other minor grain legumes. While regionally important grain legumes have received breeding attention compared to other minor grain legumes, there is still need for pre-breeding to develop new gene pools for all grain legumes. This will be followed by breeding and commercialization of cultivars that are nutrient dense and well-adapted to semi- and arid conditions. Breeding efforts and subsequent commercialization of minor grain legumes should recognize the role played by farmers in rural areas and create opportunities for meaningful access and beneficiation.

There should be more integration of indigenous and scientific knowledge to allow rural farmers to improve grain yield and quality. It has been realized that soil fertility is a constraint in rural cropping systems and that grain legumes have the ability to improve soil fertility. To improve soil fertility, legumes should be incorporated into cropping systems through relay cropping, intercropping, crop rotations or double cropping. Researchers need to make practical recommendations based on water use and water productivity of grain legumes and focus on improving crop water productivity. This should include minor grain legumes that are indigenous to semi- and arid conditions as they have been observed to be more drought tolerant when compared to major grain legumes.

1.6. Conclusions

There is a high prevalence of food and nutrition insecurity in semi- and arid tropics. Measures to increase food production should create a balance between increasing productivity, water scarcity and nutrition. The fact that grain legumes are rich sources of proteins and micronutrients suggests that they have a role to play in contributing to food and nutrition security in poor rural communities. Use of grain legumes for both human and animal consumption provides an opportunity to improve sustainability of crop-livestock systems in the semi- and arid tropics. The large diversity of grain legumes makes them adaptable to a range of environments, especially marginal agriculture production areas. However, a poorly developed and understood value chain currently limits the realization of this potential. Aspects of their breeding, seed systems, production, marketing and utilization are not well explained. This is mostly the case for minor legumes which incidentally hold the most potential for improving food and nutrition security in semi- and arid areas. Focusing on the value chain could aid researchers to identify and unlock barriers for the promotion of legumes in semi- and arid tropics. Despite the large diversity of grain legumes, research has been biased towards major grain legumes. Ironically, the minor grain legumes are the ones indigenous to semi- and arid tropics and hence are more adaptable to water-scarce conditions. There is need to increase the legume basket by adding minor grain legumes. This will also act as a buffer when major grain legumes are not successful due to drought.

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CHAPTER 3

WATER USE OF SELECTED GRAIN LEGUMES IN RESPONSE TO VARYING WATER REGIMES

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Abstract

Grain legumes have potential to contribute to food and nutritional security in water scarce areas. Information on their yield, water use and water productivity (WP) would be useful for their promotion. The aim of the study was to make a comparative assessment of adaptation, yield, water use and WP of an underutilised grain legume (bambara groundnut) and two major grain legumes (dry bean and groundnut) under rainfed, deficit and optimum irrigation conditions. Field trials were conducted during 2015/16 and 2016/17 summer seasons in KwaZulu-Natal, South Africa, using a split-plot design arranged in completely randomised blocks with three replications. Data collected included stomatal conductance, leaf area index, timing of key phenological stages and yield. Water use was calculated as a residual of the soil water balance. Water productivity was obtained as the quotient of grain yield and water use. Crops adapted to limited soil water availability through stomatal regulation and reduction in canopy size and duration. Yield, yield components and WP varied significantly ($P < 0.05$) among crop species. During 2015/16, groundnut had the highest yield and WP (10 540 kg ha^{-1} and 0.99 kg m^{-3}, respectively). During 2016/17, the highest yield and WP were observed in dry bean (2 911 kg ha^{-1} and 0.75 kg m^{-3}, respectively). For both seasons, dry bean had the lowest water use across all water treatments (143 – 268 mm). Dry bean and groundnut out–performed bambara groundnut with respect to yield, harvest index and WP. There is need for crop improvement in bambara groundnut to improve yield and WP.

Keywords: bambara groundnut; dry bean; groundnut; yield; water productivity

INTRODUCTION

Grain legumes play an integral role in the 2030 agenda for sustainable development due to their high nutritional value and various environmental and sustainability benefits (Food and Agriculture Organisation (FAO), 2016). Their promotion could alleviate the high prevalence of malnutrition reported in regions such as sub-Saharan African and South Asia where 23.2% and 34.5% of the population, respectively, is malnourished (FAO, International Fund for Agriculture Development (IFAD) & World Food Programme (WFP), 2015). In addition to the existing burden of malnutrition, these regions are expected to carry more than 70% of the world's expected two billion population growth by 2050 (Population Reference Bureau, 2014). This necessitates the need for more nutritious food to feed the growing population and alleviate malnutrition. Grain legumes are rich sources of protein and micronutrients hence increasing their production could contribute to the regions' food and nutritional requirements (Foyer et al., 2016).

Sub-Saharan Africa and South Asia are also faced with increasing aridity and water scarcity, which hinders agricultural production (Falkenmark et al., 1989; Seckler et al., 1999; Rijsberman, 2006). Current strategies on increasing food production under water limited conditions emanate from the 'more crop per drop' notion which describes the need to produce more food with the current water resources or using less water for the current food production (Passioura, 2006; Zoebl, 2006; Molden et al., 2010). This has also been referred to as 'improving water productivity'. The greatest improvements in water productivity (WP) under water scarce regions will derive from better agronomic practices, improved irrigation management and growing appropriate crops and genotypes (Passioura, 2006; Molden et al., 2010; Karrou and Oweis, 2012; Descheemaeker et al., 2013; Estrada et al., 2015).

Currently the major grain legumes dominating cropping systems in SSA and SA are soybean, groundnut and dry bean (Chibarabada et al., 2017). Major grain legumes are species that are recognized internationally regardless of their centres of diversity, occupy significant crop area, and have been subject to formal crop improvement (Chibarabada et al., 2017). These major crops have replaced underutilised grain legumes in rural cropping systems (Pasquet, 1999). Underutilised grain legumes are defined as those that have been neglected in any dimension (geographic, social, and economic) (Padulosi et al., 2002). Underutilised crops are reported to be well–adapted to water limited conditions (Ebert, 2014; Chivenge et al., 2015; Massawe et al., 2015; Mayes et al., 2012; Nyadanu and Lowor, 2015). There is talk of re-introducing them as part of diverse efforts to improve productivity of semi- and arid cropping systems (Ebert, 2014; Chivenge et al., 2015; Massawe et al., 2015; Mayes et al., 2011; Nyadanu and Lowor, 2015). Separate studies have determined yield, water use and water use efficiency of grain legumes under different environments with varying outcomes (Abayomi et al., 2008; Mabhaudhi et al., 2013; Munoz-Perea et al., 2007; Obalum et al., 2011; Patel et al., 2008). A limitation to these studies was, results were not comparable and robust to allow for comparative analyses of yield and water use of grain legumes (Annandale et al., 2012).

This study is a first to provide a comparison of major legumes and underutilised legumes to benchmark indigenous grain legumes to major grain legumes. This will allow for a robust comparison between underutilised grain legumes and major grain legumes. It will also provide substantiation that underutilised grain legumes could be explored to improve productivity in semi- and arid cropping systems. It was hypothesised that underutilised grain legumes and major grain legumes perform the same under field conditions. The objective of this study was to conduct a comparative analysis of adaptation, yield, water use and WP of a selected underutilised grain legume [bambara groundnut (*Vigna subterranea*)] and selected major grain legumes [dry bean (*Phaseolus vulgaris*) and groundnut (*Arachis hypogaea*)] under rainfed, deficit and optimum irrigation conditions in a semi-arid environment.

MATERIAL AND METHODS

Site, climate and soil

Experiments were conducted during the 2015/16 and 2016/17 summer season at the University of KwaZulu-Natal's (UKZN) Ukulinga Research Farm in Pietermaritzburg, KwaZulu-Natal, South Africa (29°37'S; 30°16'E; 750 meters above sea level). Ukulinga is classified as a subtropical climate with low risk of frost occurrence. Average annual rainfall is 694 mm, which is received mainly during the summer months (mid-October to mid-February). Winter rain (April to August) is below 75 mm hence summer is the predominant cropping season under rainfed conditions. During the summer months, average maximum temperatures are between 26°C and 28°C while minimum temperatures can be as low as 10°C (Kunz et al., 2016).

The soil was characterised as Cleveland (Soil Classification Working Group, 1991) with an effective rooting depth of 0.40 m. Soil samples were taken to the Department of Agriculture and Rural Development Fertilizer Advisory Service for analyses of nutrients, clay content and pH. Physical characteristics were obtained from Mabhaudhi et al. (2014) who used the same field (Table 1).

Table 1: Selected soil physical, chemical and textural characteristics at the experimental site.

Soil texture	**†BD**	**pH (KCl)**	**Clay**	**‡Sat**	**§FC**	**¶PWP**	**#Ksat**	**‡‡TAW**
Clay loam	g cm^{-3}		% Volumetric				mm day^{-1}	mm
	1.47	5.17	37	48.1	40.6	21	25	78.4

†BD = Bulk density; ‡Sat = Saturation; §FC = Field capacity; ¶PWP = Permanent wilting point; #Ksat = Saturated hydraulic conductivity; ‡‡TAW = Total available water.

Plant material, experimental design and management practices

Major grain legumes selected for the study were groundnut and dry bean (common bean). Groundnut, cultivar Kwarts, was sourced from Agricultural Research Council-Grain Crops Institute, Potchefstroom. Dry bean, cultivar Ukulinga, was sourced from McDonald seeds, Pietermaritzburg. The selected underutilised grain legume was a bambara groundnut landrace that was sourced from the rural area of Jozini in KwaZulu-Natal, South Africa. The selection of cultivars was based on those that are commonly used by subsistence farmers and are adapted to dryland conditions.

During 2015/16, trials were planted on the 17th of November 2015. During 2016/17, the trial was initially planted on the 16th of November 2016 but failed due to monkey attacks in December 2016. Thereafter, security measures were put in place and planting was on the 16th of January 2017. The experimental design was a split-plot design arranged in randomised complete blocks with three replications. The main plots were water regimes [(optimum irrigation (OI), deficit irrigation (DI) and rainfed (RF)] while the subplots were the three grain legume crops (dry bean, groundnut and bambara groundnut). Subplot size was 5 m × 3.75 m.

Irrigation was applied through a sprinkler system with a distribution uniformity of ≈ 85%. The sprinkler nozzles had a throw distance (radius) of 8 m. The distance between the water treatments was 12 m to avoid sprinkler overspray. Irrigation scheduling was based on management allowable depletion (MAD). Management allowable depletion was the maximum amount of total available water (TAW) allowed to be depleted from the root zone before irrigation occurs. In the OI treatment, MAD was 20% TAW. Management allowable depletion of 20% TAW is ≈ 40 % MAD of plant available water (PAW). This was based on the Alberta Irrigation Management Manual (2016), recommended management allowable depletion (MAD) for grain legumes. The approach to DI was to apply irrigation (MAD: 20% TAW) at the growth stages that were most sensitive to water stress (Geerts and Raes, 2009). The most water stress sensitive growth stages of the grain legume crop species were the flowering and pod-filling stages (Ahmed and Suliman, 2010; Vurayai et al., 2011). All the water treatments were fully irrigated up to 90% emergence to ensure establishment of all trials. In the RF trial, irrigation was withdrawn after emergence and the trial relied entirely on rainfall thereafter.

Department of Agriculture, Forestry and Fisheries (DAFF), recommended plant populations of 66 667 plants ha^{-1} for bambara groundnut and 88 889 plants ha^{-1} for dry bean and groundnut were used. The trials were planted on ploughed and rotovated land. Groundnut and dry bean were planted on furrows while bambara groundnut was planted on mounted ridges. Groundnut was ridged four weeks after planting. Seeds were treated with an insecticide (Chlorpyrifos at the rate of 0.6 g of a.i /kg of seed) and a fungicide (Mancozeb at the rate of 0.0015 g a.i per ml per 1 kg of seed) before planting. Based on results of soil analyses, an organic fertiliser, Gromor accelerator (0.3% N, 0.15% P and 0.15% K), was applied at planting at a rate of 4 000 kg ha^{-1} to meet the nutrient requirements for the grain legume crops. The trials were kept weed free through routine hand weeding using hand hoes. During weeding, bambara groundnut and groundnut were re-ridged to maintain the ridges. Kemprin (0.15 ml/15 litres water) was sprayed eight weeks after planting to control cutworm and leafhopper. Chlorpyrifos (30 ml/15 litres water) was applied nine weeks after planting to control black aphids.

Measurements

Climate data

Daily weather data [maximum (Tmax) and minimum (Tmin) air temperature (°C), rainfall (mm) and reference evapotranspiration (ET_o) (mm)] were obtained from an AWS located at the Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations.

Irrigation

The sprinkler irrigation system had an approximate application rate of 7 mm per hour. This was used to estimate irrigation run time. The actual amount of irrigation after each irrigation event was measured using rain gauges randomly placed in the experimental plots.

Soil water content

Soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). To measure soil water content the PR2/6 is inserted in pre-installed access tubes that are 1 m long. One access tube was installed in each sub-plot. The soil profile at the experiment site was shallow with an effective rooting depth of 0.40 m, hence access tubes were installed up to a depth of 0.40 m. The sensors of the PR2/6 profile probe are positioned to measure volumetric water content at six depths (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe). Since access tubes were installed up to 0.40 m deep the last two sensors of the PR2/6 positioned at 0.60 and 1.00 m were used to measure soil water content in the field at 0.10 m and 0.40 m, respectively. *Plant canopy and development*

Emergence was recorded when the hypocotyl protruded 20 mm above the soil. Leaf area index (LAI), which is the one–sided green leaf area per unit ground surface area occupied by the plant was measured weekly using the LAI-2200C Plant Canopy Analyzer (LICOR, USA). Timing of key phenological stages (emergence, flowering, podding, senescence and maturity) was done through weekly visual observations. Time to emergence was when 90% of the experimental plants had the coleoptile piercing through the soil. Time to flowering, podding, senescence and maturity was defined by 50% of the experimental plants showing visual signs. A plant was defined to be flowering when the flower fully opens. A plant was defined as podding when the first pod appears on the plant. Senescence was defined when at least 10% of leaves had senesced without new leaves being formed to replace them. A plant matured when at least 50% of leaves had senesced. Phenology data was then converted to thermal time (growing degree days) using the equation by McMaster and Wilhelm (1997); where

GDD = [(Tmax + Tmin) /2] – Tbase **Equation 1**

where; Tmax = maximum temperature (°C)

Tmin = minimum temperature (°C)

Tbase = base temperature for grain legumes (8°C).

If Tmax < Tbase then Tmax = Tbase, and if Tmin < Tbase, then Tmin = Tbase.

Physiology

Stomatal conductance was measured weekly using a Steady State Leaf Porometer Model SC-1 (Decagon Devices, USA) on the abaxial surface of a new fully expanded and fully exposed leaf.

Yield and yield components

At harvest, six representative plants of each subplot were harvested. Thereafter the plants were air dried in a controlled environment situated at the UKZN Phytosanitary Unit for 11 days until there were no changes in total biomass observed. Thereafter yield components were determined (total biomass, pod number, pod mass, grain number and grain mass). In the case of dry bean, total biomass referred to the above ground biomass while for groundnut and bambara groundnut total biomass referred to the below and aboveground biomass. Thereafter, harvest index (HI) was determined as:

$$HI = (Y_g/B) \times 100 \qquad \textbf{(Equation 2)}$$

where: HI = harvest index (%), Y_g = economic yield based on grain yield (kg), and B = total biomass (groundnut and bambara groundnut)/ above ground biomass (dry bean) (kg).

Determination of water use

Water use (WU) for each treatment was calculated as the residual of a soil water balance (Allen et al., 1998):

$$WU = P + I - D - R - \Delta SWC \qquad \textbf{(Equation 3)}$$

where: WU = water use = evapotranspiration (mm),

P = precipitation (mm),

I = irrigation (mm),

D = drainage (mm),

R = runoff (mm), and

ΔSWC = changes in soil water content (mm).

Drainage was considered as negligible since the observed impeding layer at 0.4 m restricted downward movement of water beyond the root zone. Runoff (R) was not quantified directly; however, the United States Department of Agriculture - Soil Conservation Service (USDA-SCS) procedure (USDA-SCS, 1967) was used to estimate the monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to runoff. Monthly effective rainfall was estimated using mean monthly rainfall obtained from 30-year rainfall data of Ukulinga Research Station and monthly crop evapotranspiration for the different crops estimated using the crop coefficient approach $ET_o \times Kc$ (Allen et al., 1998). The soil water balance was therefore simplified to;

$$WU = ER + I - \Delta SWC \qquad \textbf{(Equation 4)}$$

where: WU = water use = evapotranspiration (mm),

ER = effective rainfall (mm),

I = irrigation (mm), and

ΔSWC = changes in soil water content (mm).

Values of water use in mm (depth) were then converted to m^3 (volume) using the formula;

$$\text{Volume } (m^3) = \text{Area } (m^2) \times \text{Depth } (m) \qquad \textbf{(Equation 5)}$$

Determination of WP

Water Productivity was then calculated as;

$$WP = Y_a / ET \qquad \textbf{(Equation 6)}$$

where: WP is water productivity (kg m^{-3}), Y_a is the grain yield (kg) and ET is the actual evapotranspiration (m^3).

Data analyses

Data of the two seasons (2015/16 and 2016/17) were subjected to Bartlett's and Levene's tests for homogeneity of variance in GenStat® 18th Edition (VSN International, UK). Results of phenology showed homogeneity between the two seasons hence the seasons were combined during the analysis. Results of yield, LAI and stomatal conductance showed evidence of non-homogeneity of variance between the two seasons hence the seasons were analysed separately. Analysis of variance (ANOVA) was performed using GenStat® 18th Edition (VSN International, UK) at a probability level of 0.05. Least significant differences (LSD) were used to separate means. Path coefficients on the dependent variable (grain yield) were calculated separately for the two seasons in Microsoft® Excel 2016 using the method by Dewey and Lu (1959), partitioning the correlations into components direct and indirect effects.

RESULTS

Weather data and irrigation

During 2015/16, average maximum and minimum temperatures were 28°C and 16°C, respectively. Maximum temperatures ranged between 17°C and 41°C with the highest (41°C) being observed 37 days after planting (DAP). During 2016/17 maximum temperatures were slightly below that of 2015/16 ranging from 12 – 38°C. During both seasons, the maximum temperatures went above the upper thresholds (33 – 35°C) for all the grain legumes used in the study. Minimum temperatures ranged between 10°C and 21°C during 2015/16 while they went as low as 7°C during 2016/17 (Fig 1). Minimum temperatures during the 2016/17 went below the base temperature (9°C) for the grain legumes. Total rainfall during 2015/16 was 445 mm while 2016/17 received only 52% of that (235 mm). Reference evapotranspiration was also higher during 2015/16 compared to 2016/17 (516 mm and 415 mm, respectively). Based on the USDA-SCS estimations, effective rainfall for the growing months (November to May) was between 50 and 72% of the monthly rainfall.

During 2015/16, total supplementary irrigation added to the OI and DI trials was 101 mm and 40 mm, respectively, while only 18 mm supplementary irrigation was added to the RF trial to support emergence. During 2016/17, total supplementary irrigation was higher compared to the previous season with 160 mm, 86 mm and 28 mm being added to the OI, DI and RF trials, respectively.

Plant physiology

During both seasons, stomatal conductance responded significantly to the water treatments, crops and time ($P < 0.05$) (Fig 2). Stomatal conductance also fluctuated over time in response to fluctuating environmental conditions [soil water availability, air temperatures and ET_o (Fig 2 and 3)]. The OI trial had minimum water stress compared to the other water treatments. Consequently, stomatal conductance was higher in the OI trial compared to the others during both seasons (Fig 3). Weather data showed that average temperatures and rainfall were higher during 2015/16 compared to 2016/17. Stomatal conductance responded to this with higher mean stomatal conductance in all the water treatments during 2015/16 (264.5 mmol m^{-2} s^{-1}) compared to 2016/17 (168.7 mmol m^{-2} s^{-1}). The crops responded differently to varying environmental conditions with dry bean showing the highest mean conductance (316.7 mmol m^{-2} s^{-1}) while bambara had the lowest mean conductance (234.6 mmol m^{-2} s^{-1}) during 2015/16. Results of 2016/17 were contradictory with dry bean showing the lowest mean conductance (150.7 mmol m^{-2} s^{-1}) and groundnut the highest mean conductance (180 mmol m^{-2} s^{-1}).

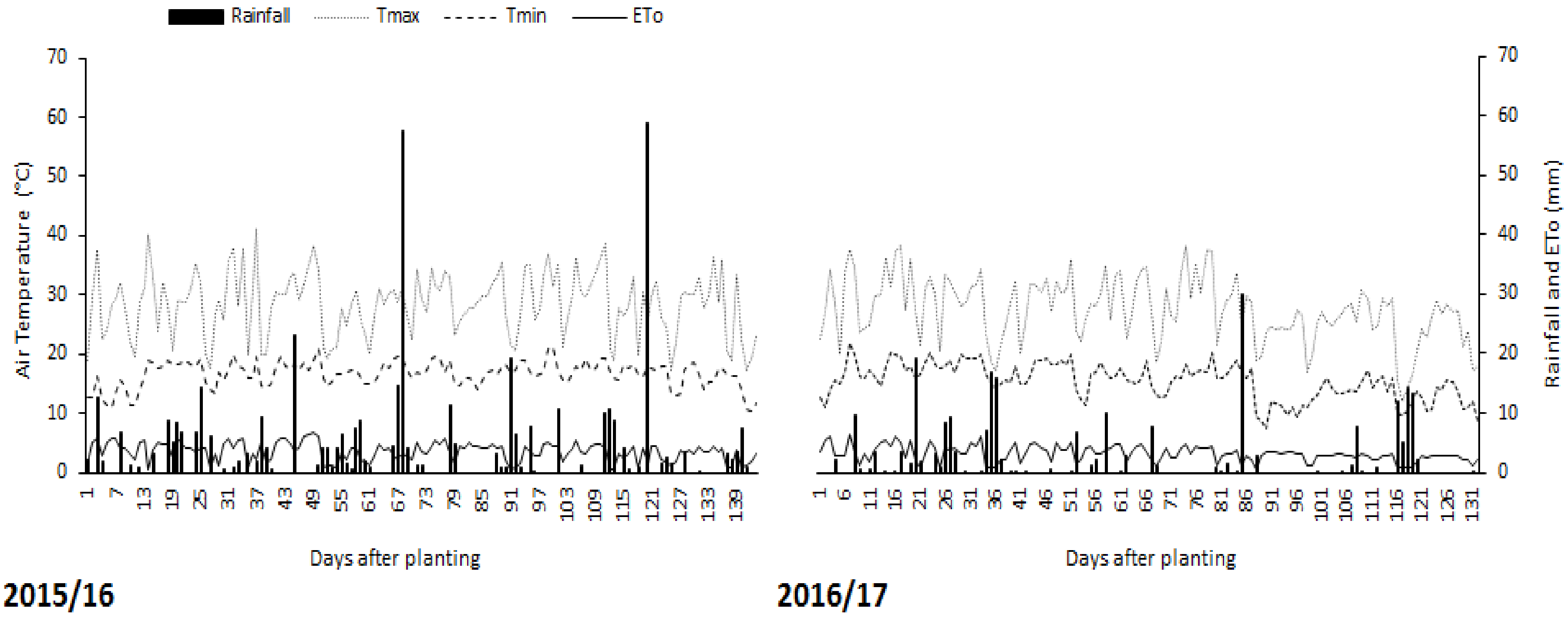

Figure 1: Maximum and minimum temperatures, rainfall and ETo observed at the study site (Ukulinga Research Farm) during the growing seasons 2015/16 and 2016/17.

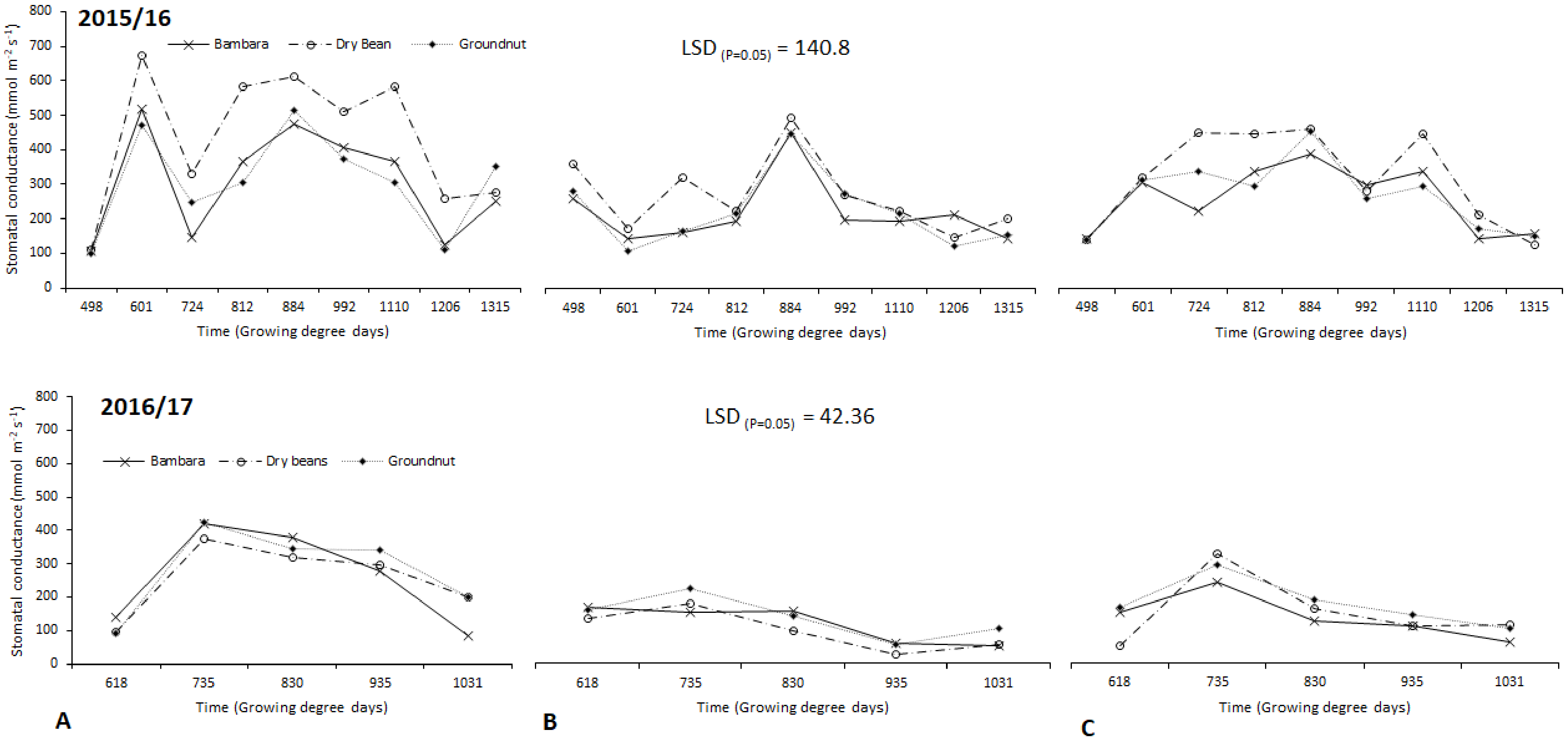

Figure 2: Stomatal conductance of three grain legumes crops (groundnut, dry bean and bambara groundnut) grown under three water treatments (A = OI B = DI and C = RF) during two growing seasons (2015/16 and 2016/17).

Plant canopy and development

Dry bean was an upright bush variety while groundnut and bambara groundnut were rosette and bushy. This, however, did not have an influence on LAI during 2015/16 as results showed no significant differences ($P > 0.05$) among the crops (Fig 3). Water treatments were also not significantly different (Fig 3). Although LAI was fluctuating the trend was that it increased from planting up to 992 and 1 206 growing degree days after planting, which coincided with podding in dry bean and both flowering and podding in groundnut and bambara groundnut. Thereafter, LAI declined as the crops started to senesce towards maturity (Fig 3 and Table 2). During 2016/17, LAI showed a different trend with results of crops, water treatments and their interaction being highly significantly different ($P < 0.001$). a comparison of canopy size between seasons showed that 2016/17 had a smaller canopy size relative to 2015/16. This was attributed to lower average temperatures and less rainfall during 2016/17. During 2016/17, dry bean emerged faster, hence LAI increased earlier, with the crop maintaining higher LAI compared to the crops throughout the season (Fig 3 and Table 2). Dry bean had less stomatal conductance but had a bigger transpiring canopy (Fig 2 and 3).

Time to all key phenological stages observed during the study (time to emergence, time to flowering, duration of flowering, time to podding, time to senescence and time to maturity) showed significant differences ($P < 0.001$) among the grain legume crops (Table 2). The water treatments influenced time to flowering and time to senescence ($P < 0.05$). With respect to season, the only results that were different ($P < 0.05$) were time to emergence, time to flowering and duration of flowering. Consistent to both seasons, dry bean was the fastest to emerge (< 120 growing degree days) while bambara groundnut was the slowest (> 205 growing degree days). This supports results of LAI where the dry bean canopy developed faster and the bambara groundnut canopy developed slower. Groundnut tended to flower and pod early extending its flowering duration for up to 35 days. Bambara groundnut also had a long flowering period but the time to flowering was later in the season (840 growing degree days) when compared to the other crops (< 642 growing degree days). Unlike bambara groundnut and groundnut, dry bean had distinct vegetative, flowering and podding stages, and consequently senesced and matured earlier. Groundnut and bambara groundnut were indeterminate and took up to 2043 growing degree days to mature. This was evident during the 2015/16 where the canopy of groundnut and bambara showed much fluctuation due to replacement of senescing leaves with new ones (Table 2 and Fig 3).

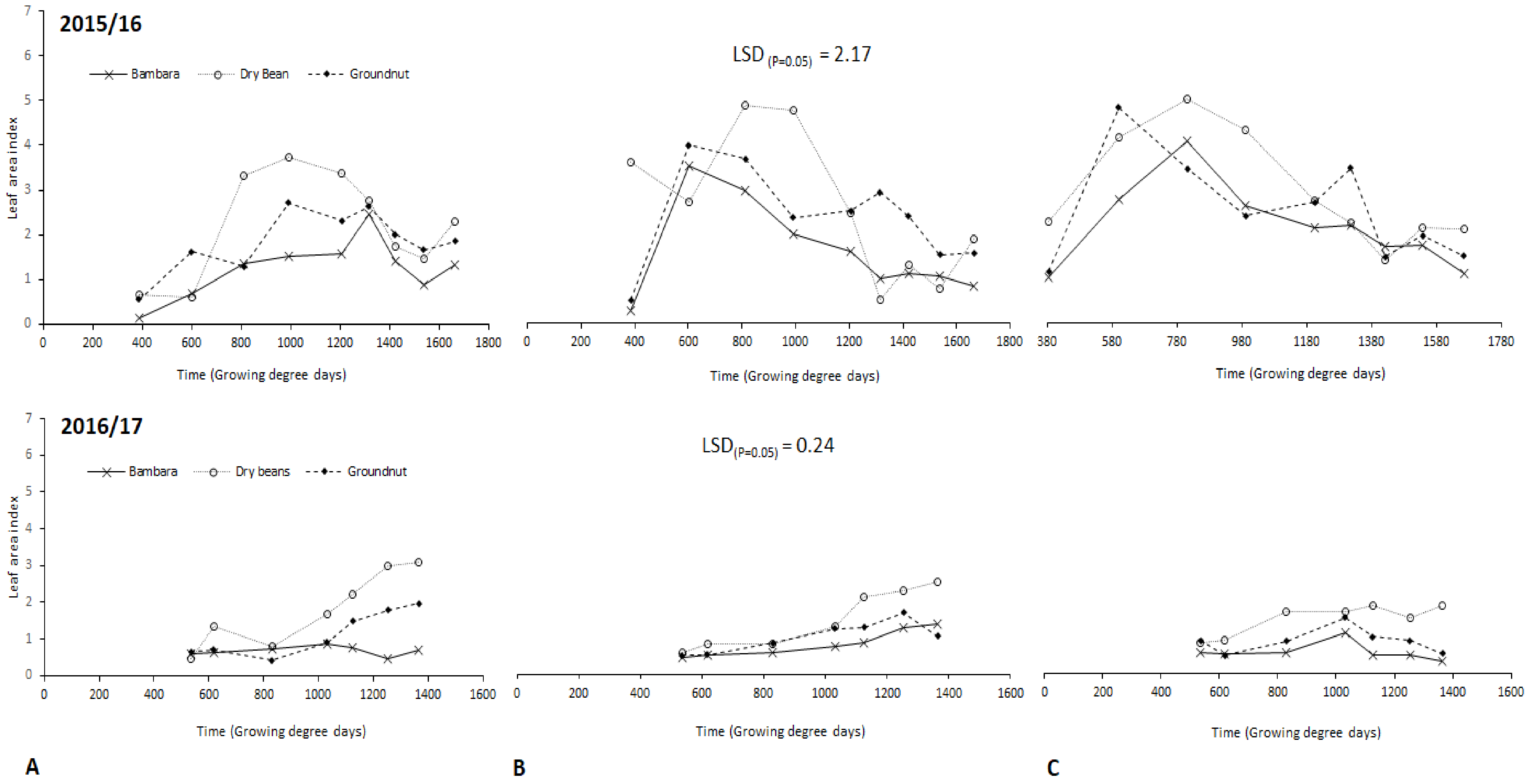

Figure 3: Leaf area index of three grain legumes crops (groundnut, dry bean and bambara groundnut) grown under three water treatments (A = OI B = DI and C = RF) during two growing seasons (2015/16 and 2016/17).

Table 2: Timing of key phenological events of three grain legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (OI, DI and RF) during two growing seasons (2015/16 and 2016/17).

		Crop	†TTE	‡TTF	§DOF	¶TTP	#TTS	‡‡TTM
			Growing Degree Days					
2015/16	OI	Dry bean	104b	812c	202d	884d	1336f	1677e
		Groundnut	117b	386d	285b	553f	1666a	1773a
		Bambara groundnut	205a	910a	295c	1143a	1682ab	1949a
	DI	Dry bean	102b	724c	233d	812d	1372e	1677d
		Groundnut	111b	386d	319c	601f	1518d	1773a
		Bambara groundnut	205a	842b	322c	1081f	1730a	1838a
	RF	Dry bean	102b	724e	206d	812e	1365f	1677e
		Groundnut	107b	386d	216c	601f	1592a	1773a
		Bambara groundnut	211a	842b	250c	1081a	1705a	1921a
2016/17	OI	Dry bean	120b	735c	261d	935e	1455d	1623d
		Groundnut	226a	618d	519a	602c	1903ab	2043b
		Bambara groundnut	258a	961a	407a	1100a	1563b	1755b
	DI	Dry bean	144b	735c	227d	774d	1368e	1583d
		Groundnut	240a	618d	380ab	686e	1267d	1942bc
		Bambara groundnut	271a	961a	360ab	1100a	1519c	1642c
	RF	Dry bean	119b	642d	244d	773d	1383f	1582e
		Groundnut	205a	376e	374a	670e	1737c	1965c
		Bambara groundnut	269a	862b	30b	1031b	1399c	1742c
Significance		Crops	<0.001	<0.001	<0.001	<0.001	< 0.001	<0.001
		Water treatment	*ns	0.040	*ns	*ns	0.007	8ns
		Season	<0.001	0.019	<0.001	*ns	*ns	*ns
		Crop × Water Treatment × Season	*ns	*ns	*ns	*ns	*ns	*ns
		LSD $_{(P=0.05)}$	27.0	120	4.5	71.0	6.5	79

†TTE = Time to emergence; ‡TTF = Time to flowering; §DOF = Duration of flowering; ¶TTP = Time to podding; #TTS Time to senescence; ‡‡TTM = Time to maturity; *ns = not significant at P = 0.05.

Yield components, water use and water productivity

During 2015/16, results of yield components (total biomass, pod number, pod mass, grain number, grain yield, HI) and WP showed highly significant differences (P < 0.001) among the crop species (Table 3). Yield components did not show any significance difference among the water treatments ($P > 0.05$). The interaction between the crops and the water regimes were only significantly different ($P < 0.05$) for pod mass, grain mass and WP (Table 3).

Groundnut had the longest season duration and the highest stomatal conductance, which translated to the highest total biomass (10 540 kg ha^{-1}). Dry bean matured earlier compared to the other crops and consequently accumulated the lowest total biomass (4 220 kg ha^{-1}). Early and prolonged flowering and podding in groundnut resulted in more pods (> 53 per plant) (Table 3). This translated to high pod yield (3 460 – 4 950 kg ha^{-1}). Although bambara groundnut also indeterminate, it podded late in the season (≈ 77 DAP) resulting in the second highest number of pods (40 – 55 per plant); however, this did not translate to gains in pod yield. Bambara groundnut had the lowest pod yield (1 650 – 2 200 kg ha^{-1}), which was less than the major legumes (dry bean and groundnut). With respect to grain yields, the major legumes were also superior to bambara groundnut. Groundnut had the highest grain yield under DI, which was 100% more than bambara groundnut (Table 3). With respect to HI, dry bean, exhibited a HI that was ≈ 45 – 50% higher than that of groundnut and bambara groundnut. Bambara groundnut, podded late into the season limiting the duration of pod filling, resulting in the lowest HI (21%) which was observed under RF conditions (Table 3).

As groundnut matured late and had the highest biomass it was expected that it would have the highest water use. Results were true to expectation with observed groundnut water use values of 319, 292 and 283 mm under OI, DI and RF conditions, respectively (Table 3). The inverse was also true as dry bean that had lowest water use of 268, 238 and 238 mm under OI, DI and RF conditions, respectively. Despite groundnut having the highest water use, it produced more grain yield, resulting in high WP (0.61 – 0.99 kg of grain per m^{-3} of water consumed). Poor grain yields for bambara groundnut resulted in the crop having the least WP (0.39 – 0.53 kg m^{-3}) (Table 3). Based on mean values of water treatments, WP improved by ≈ 12% under RF and DI conditions compared to the OI.

Statistical trends of yield components during 2016/17 followed that of 2015/16 season. Crops species showed significant differences ($P < 0.05$) while water treatments were not significantly different ($P > 0.05$) (Table 4). The interaction between the crops and the water regimes were only significantly different ($P < 0.05$) for pod yield and grain number (Table 4).

During 2016/17, higher stomatal conductance and a larger canopy (LAI) in dry bean was observed. This led to dry bean outperforming the other crops with respect to biomass, pod yield, grain yield and HI (2 911 kg ha^{-1}, 1 872 kg ha^{-1}, 1 296 ha^{-1} and 49.2%, respectively). Although groundnut produced the highest number of pods across all treatments (> 17) this did not translate to high pod yield as observed during 2015/16. Bambara groundnut continued to trail the major legumes with respect to biomass and pod yield with the least biomass and pod yield (1 346 kg ha^{-1} and 447 kg ha^{-1}, respectively) (Table 4). During 2016/17, groundnut flowered and podded late and matured earlier; consequently, it produced the lowest grain yield under DI and RF conditions (362 kg ha^{-1} and 267 kg ha^{-1}, respectively). This translated to low HI ranging between (10.5 and 24.2 %), which was ≈ 50 to 300% less than dry bean (Table 4).

Results of 2016/17 showed that despite dry bean producing the highest biomass, it had the lowest water use (143 – 195 mm) compared to the other crops (Table 4); this accounted for high WP (0.66 – 0.75 kg m^{-3}). Consistent to results of 2015/16, groundnut had the highest water use across all the water treatments (249 – 345 mm) (Table 4). A combination of low grain yield and high water use observed in groundnut led to the lowest WP (0.08 – 0.16 kg m^{-3}). Bambara groundnut's WP slightly higher than that of groundnut (0.12 – 0.17 kg m^{-3}) (Table 4).

Path coefficient analysis for grain yield

During 2015/16, groundnut had the highest grain yield. Based on results of path coefficient analysis, the high pod number of groundnut had highest contribution to the grain high. Early flowering and longer flowering duration observed in groundnut also contributed to grain yield (0.658 and 0.563, respectively). Bambara groundnut had the lowest yield and results of path analysis showed that grain number had the highest contribution to the observed grain yield. Path coefficient analysis also showed that for bambara groundnut the lengthy time to emergence and podding contributed negatively to grain yield (-8.811E-13). For dry bean, path coefficient analysis for 2015/16 showed that time to flowering had the highest direct contribution to grain yield (1.670) (Table 5). During 2016/17, dry bean had the highest yield and results of path coefficient analysis suggest that biomass (4.166) and duration of flowering (3.342) positively contributed to this (Table 6).

Table 3: Yield and yield parameters (total biomass, pod number, pod mass, grain number, grain mass and harvest index), water use and water productivity of three legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (OI, DI and RF) during the 2015/16 season.

Water treatments	Crop species	Total biomass	Pod number	Pod yield	Grain number	Grain yield	Harvest index	Water use	Water Productivity
		kg ha^{-1}	Plant $^{-1}$	kg ha^{-1}	Plant $^{-1}$	kg ha^{-1}	%	mm	kg m^{-3}
OI	Dry bean	5040c	24c	3460b	64b	2260ab	43.26a	268	0.84a
	Groundnut	8020b	55a	3360b	77a	1950a	23.54b	316	0.61b
	Bambara groundnut	6030bc	53a	2200b	46b	1480b	24.53b	317	0.47b
	Mean	**6360**	**44**	**3000**	**63**	**1800**	**30.44**	**302**	**0.64**
DI	Dry bean	4220c	19c	2080bc	40b	1400b	35.66a	239	0.62ab
	Groundnut	10540a	68a	4960a	106a	2900a	27.73b	292	0.99a
	Bambara groundnut	6390b	40bc	2170b	45b	1410b	22.41b	263	0.53b
	Mean	**7050**	**42**	**3070**	**64**	**1930**	**28.60**	**265**	**0.71**
RF	Dry bean	5280c	22c	2890b	50b	1960a	37.15a	238	0.82a
	Groundnut	9650ab	69a	4570ab	100a	2770a	28.63b	283	0.98a
	Bambara groundnut	5000c	44b	1650c	39b	1090b	21.16b	277	0.39b
	Mean	**6650**	**45**	**3040**	**63**	**1940**	**28.98**	**266**	**0.73**
Significance (P=0.05)	Crops	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001		< 0.001
	Water regime	*ns	*ns	*ns	*ns	*ns	*ns		*ns
	Crops × Water regime	*ns	*ns	0.009	*ns	0.031	*ns		0.041
	LSD $_{(P=0.05)}$	2130	17	1361	33	1069	9.35		0.37

*ns = not significant at P = 0.05. Since pods and grain were counted as whole numbers, only discreet values of pod and grain number are presented.

Table 4: Yield and yield parameters (total biomass, pod number, pod mass, grain number, grain mass and harvest index), water use and water productivity of three legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (OI, DI and RF) during the 2016/17 season.

Water treatments	**Crop species**	**Total biomass**	**Pod number**	**Pod yield**	**Grain number**	**Grain yield**	**Harvest index**	**Water use**	**Water Productivity**
		kg ha^{-1}	Plant $^{-1}$	kg ha^{-1}	Plant $^{-1}$	kg ha^{-1}	%	mm	kg m^{-3}
OI	Dry bean	2730a	11b	1872a	30a	1296a	49.2a	195	0.66a
	Groundnut	2681a	30a	1123ab	35a	585b	24.2b	345	0.16b
	Bambara groundnut	1371b	13b	545b	14b	466b	26.8b	306	0.15b
	Mean	**2261**	**18**	**1180**	**26**	**782**	**33.4**	**282**	**0.32**
DI	Dry bean	2911a	11b	1843a	31a	1098a	37.8a	163	0.67a
	Groundnut	2359ab	21ab	751b	19b	362b	10.5b	280	0.08b
	Bambara groundnut	1387b	15b	736b	21ab	402b	32.5a	256	0.17b
	Mean	**2219**	**16**	**1110**	**24**	**592**	**32.3**	**233**	**0.31**
RF	Dry bean	2543ab	13b	1409a	29a	1081a	42.6a	143	0.75a
	Groundnut	2148a	17b	537b	18b	267b	12.7b	249	0.10b
	Bambara groundnut	1346b	12b	447b	17b	292b	18.8b	232	0.12b
	Mean	**2013**	**14**	**798**	**21**	**547**	**24.7**	**208**	**0.2**
Significance (P=0.05)	Crops	0.012	0.004	< 0.001	< 0.001	< 0.001	< 0.001		< 0.001
	Water regime	ns	ns	ns	ns	ns	ns		ns
	Crops × Water regime	ns	ns	0.009	0.015	ns	ns		ns
	LSD$_{(P=0.05)}$	1265	10.66	762.7	12.05	538.5	18.8		0.26

ns = not significant at P = 0.05. Since pods and grain were counted as whole numbers, only discreet values of pod and grain number are presented.

Table 5: Path coefficient analysis showing direct (diagonal in bold) and indirect effects of independent variables on grain yield of dry bean, groundnut and bambara groundnut grown under three water treatments (OI, DI and RF) during the 2015/16 season.

Dry Bean												
	†DOF	**‡HI**	**§PY**	**¶PN**	**#GN**	**‡‡TTE**	**††TTF**	**§§TTM**	**¶¶TTP**	**##TTS**	**Biomass**	**Water use**
†DOF	**-0.457**	-0.078	0.302	-0.133	-0.065	0.057	-1.321	0.141	0.618	0.007	0.340	0.935
‡HI	0.158	**0.226**	0.436	-0.149	-0.110	0.000	0.152	0.079	0.068	-0.017	0.158	-0.420
§PY	-0.158	0.113	**0.873**	-0.277	-0.183	-0.033	-0.609	0.197	0.391	-0.013	0.556	0.060
¶PN	-0.198	0.109	0.785	**-0.308**	-0.177	0.033	-0.609	0.159	0.340	-0.008	0.616	0.240
#GN	-0.158	0.132	0.760	-0.287	**-0.189**	0.033	-0.609	0.197	0.391	-0.014	0.550	0.060
‡‡TTE	0.072	0.000	0.071	0.028	0.017	**-0.364**	0.000	0.050	0.186	-0.009	-0.060	0.000
††TTF	0.361	0.021	-0.287	0.112	0.069	0.000	**1.670**	-0.161	-0.838	0.002	-0.298	-0.985
§§TTM	0.250	-0.069	-0.600	0.189	0.145	0.070	1.670	**-0.258**	-0.689	0.017	-0.342	-0.348
¶¶TTP	0.310	-0.017	-0.337	0.115	0.081	0.074	1.043	-0.258	**-0.911**	0.009	-0.250	-0.804
##TTS	-0.121	-0.142	-0.381	0.092	0.098	0.119	1.534	-0.195	-0.295	**0.026**	-0.086	0.306
Biomass	-0.238	0.055	0.671	-0.291	-0.160	0.033	0.155	-0.162	0.350	-0.003	**0.651**	0.391
Water use	0.375	0.083	-0.042	0.065	0.010	0.000	-0.765	0.135	-0.644	-0.007	-0.224	**-1.137**
Groundnut												
†DOF	**0.645**	0.017	0.000	0.270	-0.326	-0.155	-0.018	-0.086	-0.345	-0.079	0.035	0.078
‡HI	-0.048	**-0.233**	0.223	1.452	-0.811	0.035	-0.028	0.097	0.154	0.107	0.040	-0.139
§PY	0.000	-0.140	**0.370**	1.095	-0.762	-0.366	-0.010	0.073	0.233	0.119	0.204	-0.064
¶PN	0.096	-0.186	0.223	**1.815**	-1.123	-0.208	-0.019	0.015	0.154	0.025	0.150	-0.093
#GN	0.168	-0.151	0.226	1.634	**-1.248**	-0.208	-0.015	0.002	0.232	0.041	0.205	-0.069
‡‡TTE	-0.152	-0.012	-0.206	-0.574	0.394	**0.658**	-0.020	0.017	0.000	0.006	-0.216	0.000

††TTF	0.128	-0.069	0.039	0.378	-0.197	0.144	**-0.093**	0.052	0.046	0.063	0.013	-0.096
§§TTM	0.265	0.108	-0.130	-0.127	0.011	-0.055	0.023	**-0.209**	-0.122	-0.214	-0.052	0.152
¶¶TTP	-0.395	-0.064	0.153	0.497	-0.513	0.000	-0.008	0.045	**0.563**	0.096	0.130	-0.095
##TTS	0.221	0.109	-0.193	-0.201	0.223	-0.018	0.025	-0.195	-0.237	**-0.229**	-0.107	0.142
Biomass	0.072	-0.029	0.241	0.866	-0.815	-0.452	-0.004	0.035	0.233	0.078	**0.314**	-0.029
Water use	0.228	0.147	-0.108	-0.766	0.394	0.000	0.041	-0.145	-0.244	-0.148	-0.041	**0.219**
Bambara Groundnut												
†DOF	**-1.251E-12**	9.845E-13	8.660E-01	-3.055E-12	-1.100E-13	1.366E-13	-2.784E-13	0.000E+00	-1.153E-13	-1.550E-13	3.151E-13	1.012E-13
‡HI	-5.415E-13	**2.274E-12**	7.000E-01	-2.616E-12	6.337E-14	-1.841E-13	-1.207E-13	9.045E-14	-4.093E-15	-5.116E-14	3.106E-13	9.754E-14
§PY	-1.083E-12	1.592E-12	**1.000E+00**	-3.793E-12	-1.908E-13	1.930E-13	-2.414E-13	6.534E-14	-5.048E-14	-1.791E-13	4.243E-13	3.880E-14
¶PN	-9.742E-13	1.517E-12	9.670E-01	**-3.922E-12**	-2.542E-13	2.634E-13	-2.414E-13	4.536E-14	-2.228E-14	-1.875E-13	4.470E-13	-1.958E-14
#GN	1.976E-13	2.069E-13	-2.740E-01	1.432E-12	**6.963E-13**	-2.405E-13	-2.203E-13	5.508E-14	4.411E-14	7.009E-14	-1.660E-13	0.000E+00
‡‡TTE	1.938E-13	4.752E-13	-2.190E-01	1.173E-12	1.901E-13	**-8.811E-13**	5.049E-13	2.700E-14	-1.264E-13	5.090E-14	-1.719E-13	2.675E-13
††TTF	-3.952E-13	3.115E-13	2.740E-01	-1.075E-12	1.741E-13	5.049E-13	**-8.811E-13**	-4.131E-14	9.936E-14	-3.504E-14	1.246E-13	-1.600E-13
§§TTM	0.000E+00	-7.617E-13	-2.420E-01	6.589E-13	-1.421E-13	8.811E-14	-1.348E-13	**-2.700E-13**	-4.547E-15	8.569E-14	-1.019E-13	6.540E-14
¶¶TTP	6.340E-13	-4.093E-14	-2.220E-01	3.844E-13	1.351E-13	4.899E-13	-3.850E-13	5.400E-15	**2.274E-13**	5.218E-14	1.228E-14	-2.694E-13
##TTS	-7.578E-13	4.547E-13	7.000E-01	-2.875E-12	-1.908E-13	1.753E-13	-1.207E-13	9.045E-14	-4.638E-14	**-2.558E-13**	3.033E-13	-7.796E-14
Biomass	-8.666E-13	1.553E-12	9.330E-01	-3.856E-12	-2.542E-13	3.330E-13	-2.414E-13	6.048E-14	6.139E-15	-1.706E-13	**4.547E-13**	-5.838E-14
Water use	-3.427E-13	6.003E-13	1.050E-01	2.079E-13	0.000E+00	-6.379E-13	3.815E-13	-4.779E-14	-1.658E-13	5.397E-14	-7.185E-14	**3.695E-13**

†DOF = Duration of flowering; ‡HI = Harvest index; §PY = Pod yield; ¶PN = Pod number; #GN = Grain number; ‡‡TTE; Time to emergence = ††TTF = Time to flowering; §§TTM = Time to maturity; ¶¶TTP = Time to podding, ##TTS = Time to senescence

Table 6: Path coefficient analysis showing direct (diagonal in bold) and indirect effects of independent variables on grain yield of dry bean, groundnut and bambara groundnut grown under three water treatments (OI, DI and RF) during the 2016/17 season.

	Biomass	**†DOF**	**‡HI**	**§PN**	**¶PY**	**#GN**	**‡‡TTE**	**††TTF**	**§§TTM**	**¶¶TTP**	**##TTS**	**Water use**
Dry Bean												
Biomass	**4.166**	1.447	0.029	-0.202	0.677	0.323	0.057	-0.046	-0.003	-0.156	-0.093	0.246
†DOF	1.804	**3.342**	-0.023	-0.167	0.255	0.039	0.118	0.018	-0.001	-0.190	-0.008	0.000
‡HI	-0.904	0.578	**-0.134**	0.221	0.024	-0.030	0.011	-0.003	-0.001	-0.156	-0.002	0.164
§PN	2.196	1.454	0.077	**-0.383**	0.266	0.238	0.046	0.014	0.002	0.106	0.029	-0.309
¶PY	3.820	1.156	-0.004	-0.138	**0.738**	0.376	0.000	-0.035	-0.002	-0.101	-0.076	0.205
#GN	2.987	0.291	0.009	-0.202	0.615	**0.451**	-0.034	-0.018	0.000	0.073	-0.038	-0.041
‡‡TTE	0.775	1.293	-0.005	-0.057	0.000	-0.051	**0.306**	-0.019	-0.002	0.021	-0.003	-0.183
††TTF	2.016	-0.635	-0.004	0.056	0.269	0.087	0.062	**-0.095**	-0.006	-0.256	-0.127	0.539
§§TTM	1.521	0.311	-0.020	0.113	0.197	0.012	0.061	-0.066	**-0.008**	-0.328	-0.171	0.613
¶¶TTP	1.321	1.293	-0.043	0.082	0.151	-0.067	-0.013	-0.049	-0.005	**-0.492**	-0.119	0.687
##TTS	2.162	0.147	-0.001	0.062	0.314	0.096	0.006	-0.068	-0.008	-0.327	**-0.179**	0.648
Water use	1.316	0.000	-0.028	0.152	0.195	-0.024	-0.072	-0.066	-0.006	-0.435	-0.149	**0.777**
Groundnut												
Biomass	**2.334**	0.416	-0.523	-0.447	0.128	-0.129	-0.457	-0.407	0.203	-0.913	-0.293	0.130
†DOF	-0.803	**-1.210**	0.836	0.524	-0.105	0.770	0.443	0.296	-0.241	0.332	-0.428	0.000
‡HI	-0.801	-0.663	**1.525**	-0.254	0.397	1.124	0.207	-0.162	-0.037	0.183	-0.907	0.258
§PN	0.546	0.332	0.203	**-1.912**	0.589	0.726	-0.234	-0.567	0.360	0.363	-0.468	0.431
¶PY	0.390	0.166	0.789	-1.466	**0.768**	0.844	-0.153	-0.811	0.309	0.000	-0.698	0.517
#GN	-0.215	-0.666	1.225	-0.992	0.463	**1.399**	0.285	-0.203	0.070	0.091	-0.952	0.361

‡‡TTE	-1.055	-0.531	0.313	0.444	-0.116	0.395	**1.010**	0.390	-0.194	-0.486	0.089	-0.092
††TTF	1.015	0.382	0.264	-1.158	0.665	0.304	-0.421	**-0.936**	0.324	-0.105	-0.432	0.448
§§TTM	1.144	0.706	-0.136	-1.661	0.572	0.236	-0.474	-0.733	**0.414**	0.097	-0.338	0.397
¶¶TTP	1.214	0.229	-0.159	0.396	0.000	-0.073	0.280	-0.056	-0.023	**-1.756**	0.000	0.000
##TTS	0.574	-0.434	1.161	-0.751	0.450	1.118	-0.076	-0.340	0.118	0.000	**-1.191**	0.316
Water use	0.556	0.000	0.723	-1.512	0.728	0.926	-0.171	-0.770	0.302	0.000	-0.692	**0.545**
Bambara Groundnut												
Biomass	**2.586**	-0.105	0.467	0.656	-1.814	0.160	-0.260	-0.073	-0.557	-0.035	-0.066	-0.039
†DOF	0.592	**-0.458**	0.336	0.413	-0.508	-0.062	-0.220	-0.795	-0.144	0.244	0.180	0.876
‡HI	1.971	-0.251	**0.613**	0.628	-1.482	0.121	-0.386	-0.291	-0.184	0.129	-0.065	0.080
§PN	2.250	-0.251	0.511	**0.754**	-1.699	0.112	-0.361	-0.435	-0.370	0.085	0.033	0.320
¶PY	2.532	-0.125	0.491	0.691	**-1.852**	0.183	-0.266	-0.291	-0.475	0.032	-0.033	0.080
#GN	1.234	0.084	0.221	0.253	-1.011	**0.335**	-0.025	-0.439	0.013	0.037	-0.182	-0.041
‡‡TTE	-1.192	0.178	-0.421	-0.483	0.874	-0.015	**0.563**	0.078	0.155	-0.041	0.000	-0.214
††TTF	0.119	-0.229	0.112	0.207	-0.339	0.092	-0.028	**-1.589**	-0.144	0.399	0.359	1.315
§§TTM	1.438	-0.066	0.113	0.278	-0.878	-0.004	-0.087	-0.229	**-1.002**	0.019	0.207	0.633
¶¶TTP	-0.197	-0.246	0.175	0.141	-0.132	0.027	-0.051	-1.395	-0.042	**0.454**	0.350	1.156
##TTS	-0.336	-0.162	-0.079	0.049	0.120	-0.120	0.000	-1.124	-0.409	0.313	**0.507**	1.239
Water use	-0.067	-0.264	0.032	0.159	-0.098	-0.009	-0.079	-1.376	-0.418	0.346	0.414	**1.519**

†DOF = Duration of flowering; ‡HI = Harvest index; §PN = Pod number; ¶PY = Pod number; #GN = Grain number; ‡‡TTE = Time to emergence = ††TTF = Time to flowering; §§TTM = Time to maturity; ¶¶TTP = Time to podding; ##TTS = Time to senescence

DISCUSSION

Adaptation to varying water regimes

Results of SWC were such that OI > DI > RF (data not shown). Soil water content ranged between 0 and 60% of TAW in the DI and RF trials while the OI trial maintained SWC above 50% TAW (data not shown). In response to low soil water availability the crops regulated stomatal conductance to minimize water loss through transpiration. Canopy expansion was also regulated under limited soil water availability as a strategy to minimize surface area for transpiration and minimize water loss. The grain legumes under study also exhibited drought escape through hastening of key phenological stages (flowering, podding and maturity) under RF and DI conditions. In addition to the morpho-physiological adjustments, the crops could have acclimatised to limited soil water availability through osmotic adjustment allowing for maintenance of high tissue water potential and integrity of photosynthetic apparatus. This has also been observed by other studies on grain legumes, in which dry bean (El-Tohamy, et al., 2013), castor bean (*Ricinus communis*) (Shi et al, 2014), bambara groundnut (Chibarabada et al., 2015a; Collinson et al, 1997) and groundnut (Bennet et al., 1984) were exposed to long periods of water stress and were able to adjust osmotically, maintaining turgor, high leaf water potential and photosynthetic functions.

Effect of water regimes on yield, water use and water productivity

Stomatal conductance is the rate of passage of carbon dioxide (CO_2) entering, or water vapor exiting through the stomata of a leaf. Stomatal conductance is linked with transpiration and photosynthesis (Whitehead et al., 1983; Pearcy et al., 2000). Under limited soil water availability, stomatal conductance was regulated to minimize water loss through transpiration. Consequently, carbon dioxide entering the plant was lowered and this had negative effects on photosynthesis and biomass accumulation. In this study, yield and yield components were not significantly affected by water treatments. This is contrary to results of several studies that have shown water treatments to significantly affect yield of grain legumes (Acosta Gallegos and Kohashi Shibata, 1989; Mabhaudhi et al., 2013). A possible explanation to these contradictory findings could be due to the cultivars used in the study and how water stress was imposed relative to this study. The cultivars used in the study showed suitability for rainfed conditions implying that with proper cultivar selection, grain legumes can be successfully grown under dryland conditions.

Conserved water use was observed under limited soil water availability but this was not at the expense of yield and yield components. This implies that under limited soil water availability, photosynthesis was more efficient compared to OI. This was supported by results of WP which improved by ≈ 12% under RF and DI conditions during 2015/16. Improvement in WP was achieved through reduction in water use (denominator) as yield was relatively similar (numerator). This supports the recommendations by several authors to apply DI to maximise crop WP (Fereres and Soriano, 2007; Hirich et al., 2011; Rodrigues and Pereira, 2009; Sarwar and Perry, 2002; Zwart, 2013). During 2016/17, despite conserved water use under limited soil water availability and no significant differences in yield among water treatments, WP did not improve. During that season, there was poor canopy development that led to significant unproductive water loss through soil evaporation (E_s). Water use comprised significant E_s hence there was no gain in WP despite the crop's attempt to conserve water use under limited soil water availability. Under these circumstances strategies to minimize soil evaporation such as mulching, intercropping, and increasing plant density should be considered.

Crop performance

Among the three crops, dry bean was determinate while groundnut and bambara groundnut were indeterminate. Determinacy was based on cessation of vegetative growth when the terminal flower of the main stem started to develop (Sablowski, 2007). This explains the observed differences in timing of phenological stages. Groundnut and bambara groundnut took more than 132 days to mature while dry bean took less than 116 days to mature. The differences in maturation time can be explored in situations where length of the season has a significant effect on growth of yield of crops. This was observed during 2016/17 where dry bean was able to produce reasonable yield under late planting. Dry bean would be a more suitable crop for short seasons, late planting or crop rotation within the same season. Groundnut and bambara groundnut were late maturing, and during 2016/17 where planting was late, yield was poor. This could be due to unfavourable reproductive growth caused by the observed low temperatures in autumn (March to May) that went below the base temperatures for the grain legumes. This study confirms findings by Sinefu (2011) who observed significant yield reduction in bambara groundnut when it was planted in January relative to November. For late maturing varieties of grain legumes, early planting is recommended as late planting is not favourable for high yield.

Time to maturity also influences total water use with late maturing crops using more water than early maturing crops (Parker, 2009). This was the case in this study — water use was higher in groundnut and bambara groundnut which matured late. Canopy characteristics also influenced crop water use. A bigger canopy with a longer season had higher water use and biomass. This was the case for groundnut during 2016/17. Water use in bambara groundnut was also high but this was not matched by a large canopy and high biomass. Bambara groundnut showed a positive attribute for water limited conditions — it had the lowest stomatal conductance under all the water regimes compared to the other crops. Although this may have negative implications on biomass production, it is a favourable attribute as it results in conserved water use. Conserved water use through low stomatal conductance was masked by the smaller canopy and long duration that could have led to significant unproductive water loss through E_s. This implies that high water use observed in bambara groundnut included significant E_s.

The hypothesis of the study was rejected as the major grain legumes had higher yield and WP compared to bambara groundnut. For successful promotion of underutilised grain legumes there is need for crop improvement to improve yield and WP. Results of path coefficient analysis revealed the need for continuous selection in landraces as bambara groundnut showed no clear pattern of attributes that contributed to high grain yield. For the same crop, path coefficient analysis showed that the lengthy time the crop took to emerge, flower and pod negatively contributed to grain yield. Comparing bambara groundnut with groundnut, a similar crop with the same indeterminate characteristic, bambara groundnut started flowering ≈ 35 days after groundnut had already started flowering. Bambara groundnut had less time for yield formation and this could be the reason for the observed yield inferiority. This could also be the reason for the low HI in bambara groundnut. Chibarabada et al. (2015b) and Mabhaudhi et al. (2013) also reported poor yield and low HI in bambara groundnut. They attributed this to the use of landraces. This study showed that poor canopy development and lengthy time to reproductive stages contributed to the observed poor yield and low HI of bambara groundnut.

Compared to the other crops under study, dry bean had a significantly higher HI — a favourable trait indicating the plants' ability to convert biomass to economic yield more efficiently than groundnut and bambara groundnut. This could be due to the determinate behaviour of the variety, hence the crop focussed on yield formation and not vegetative growth after flowering. Determinant varieties have generally higher harvest indices as most crop resources are diverted to grain once flowering commences (De Costa et al., 1997; Unkovich et al., 2010). This was, in-part, supported by results of path coefficient analysis where time to flowering and biomass had the highest positive contribution on grain yield of dry bean. Path coefficient analysis also showed that time to podding, senescence and maturity had a negative contribution on grain yield of dry bean and groundnut. This implies that under water stress and unfavourable environmental conditions where the crop hastens phenological events it may have significant negative implications on grain yield. This was confirmed by results of the 2016/17 season where yield was dropped following unfavourable temperature and rainfall.

During 2015/16, the highest WP values were observed for groundnut (0.61 – 0.99 kg m^{-3}) and the lowest WP values were observed for bambara groundnut (0.39 – 0.53 kg m^{-3}). This contradicts Chibarabada et al. (2015b) who reported that bambara groundnut was more water use efficient than groundnut. This was based on WUE values that had been obtained in separate studies under different environmental and management conditions. This justifies the need for comparative studies under the same environment and management as WUE is greatly influenced by environment and management practices. During 2016/17, dry bean was more productive (0.66 – 0.75 kg m^{-3}) while groundnut was less productive (0.08 – 0.16 kg m^{-3}). The decrease in WP observed in groundnut during 2016/17 was as a result of poor grain yield and not water use, as water use relatively did not change compared to the previous season. This highlights the importance of proper management decisions such as planting date and crop choice as it has implications on food security and crop productivity.

CONCLUSION

Despite the two cropping seasons being heterogenous, the trend in plant adaptation to water regimes was similar for both seasons. Water use was lower under limited soil water availability relative to OI. Despite this, the crops produced reasonable yields under DI and RF conditions. This led to improvements in WP under DI and RF conditions. This implies suitability of grain legumes for production in water scarce areas. Results from this study suggest that there is scope to increase food production under RF systems. For bambara groundnut, despite low stomatal conductance, water use was high. This was because of poor canopy development that led to significant unproductive water use through E_s. Consistent to both seasons, major legumes outperformed bambara groundnut with respect to yield, HI and WP, hence the hypothesis of the study was rejected. This highlights the need for crop improvement in bambara groundnut to make it attractive for farming. This should include improving canopy development and shortening the time to reproductive stages. The grain legume crops exhibited different characteristics that contributed to yield and water use. For groundnut, late maturity led to high water use which translated to high biomass; early flowering and podding also contributed to high yields. For dry bean, early maturity led to low water use. Dry bean also had high grain yield, which translated to high HI and WP. Bambara groundnut had the lowest stomatal conductance compared to the other crops. Breeders could tap into the different characteristics for development of high yielding varieties of grain legumes. The poor performance of bambara groundnut is evidence of lack of crop improvement relative to the major legumes as landraces are a mixture of genotypes with highly diverse populations both between and within them, making it challenging to assess their performance. This study showed that despite the semi- and arid tropics being the centre of diversity for underutilised grain legumes, this does not necessarily translate to high yield and WP. While bambara groundnut showed low stomatal conductance — a desirable attribute for water limited areas, this was masked by poor canopy development which led to significant water loss through $E_{s.}$ There is need for breeding efforts to improve underutilised grain legumes and make them more attractive for farming.

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CHAPTER 4

ADAPTATION AND PRODUCTIVITY OF SELECTED GRAIN LEGUMES IN CONTRASTING ENVIRONMENTS OF KWAZULU-NATAL, SOUTH AFRICA

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Abstract

Underutilised grain legumes are being promoted as part of crop diversification efforts. However, the lack of comparable information to major legumes is limiting these efforts. A benchmarking study was conducted to compare development and productivity of selected underutilised (bambara groundnut and cowpea) and major (groundnut and dry bean) grain legumes under varying environments in KwaZulu-Natal, South Africa during the 2015/16 and 2016/17. A completely randomised block design with three replications was used at all sites. Crop phenology, yield, water use (ET) and water productivity (WP) were determined for the crops. Data were analysed separately using ANOVA. Biplot analysis was done using GGE. Bambara groundnut was slow to emerge across sites and seasons (> 17 DAP). Dry bean was early maturing (< 111 DAP) while groundnut and bambara groundnut were late maturing (> 126 DAP). Yield varied significantly ($P < 0.05$) across environments and seasons. For all environments, dry bean had the lowest ET (208 – 313 mm); bambara groundnut had the highest ET (437 mm) recorded during 2015/16. The highest and lowest WP (0.98 and 0.12 kg m^{-3}, respectively) were observed for groundnut. Cowpea had the most stable WP (0.28 – 0.38 kg m^{-3}). Based on mean values, the major legumes out-yielded the underutilised grain legumes. The potential of underutilised grain legumes was limited to particular environments. There is need for investments in improving yield of underutilised grain legumes.

Keywords: bambara groundnut; cowpea; dry bean; evapotranspiration; groundnut; water productivivity

1.1 Introduction

High prevalence of food and nutritional security remains a threat to sustainable development in the semi- and arid tropics. Approximately 70% of the population depend on agriculture for food and livelihood (FAO, 2015). Their cropping systems are predominantly starch-based and mostly feature cereals and root and tuber crops. Grain legumes often play second or third fiddle, and their contribution to food and nutrition is minimal. This is despite that they offer solutions to nutritional security and soil fertility due to their high protein content and ability to fix nitrogen (Foyer et al., 2016). The neglect has been attributed to poor and unstable yields, which make them unattractive for subsistence farming. Yield improvements in grain legumes will make them more attractive which will lead to an increase in production and consumption (Gharti et al., 2014).

Yield potential is a function of the interaction between the genotype × environment × management (G × E × M) (Tittonell and Giller, 2013). Yield of grain legumes varies significantly among species and shows low and high yield extremes under different environments (Cernay et al., 2016). Multi-environment trials on grain legume genotypes showed that they performed differently across environments. Some genotypes had greater yield stability than others (Arshad et al., 2003; Asfaw et al., 2012; Sabaghnia et al., 2012; Getachew et al., 2015). For example, dry bean genotypes were more adapted to areas with ≈ 750 mm annual rainfall and average maximum temperatures of 28°C. Mungbean genotypes were well adapted to environments with ≈ 970 mm annual rainfall and eutric soils. Therefore, an understanding of the G × E is useful to yield maximisation in grain legumes.

Studies on G × E effect on yield of grain legumes have often looked at different varieties of the same species. There have been few comparative studies that would be useful for benchmarking crop species. Among the diverse group of grain legume species, only a few dominate cropping systems (soybean, dry bean and groundnut). The poor and unstable yields observed in semi- and arid tropics could be as a result of adoption of inappropriate crop choices for the environment. This has sparked interest into underutilised grain legumes. Advocates of underutilised crops argue that, underutilised grain legumes occupy certain niches in the semi- and arid region, hence may exhibit greater yield stability across a range of environments in that region.

It was hypothesised that crop species differ in their sensitivity to environmental changes. It was further hypothesised that underutilised grain legumes could be more stable and well adapted across environments in the semi- and arid tropics since they have evolved and undergone natural and farmer selection in these environments. There is however limited evidence supporting the adaptability of underutilised legumes to semi-arid environments. In addition, there is lack of comparable, robust and conclusive empirical information comparing underutilised grain legumes to major grain legumes. There is need to benchmark underutilised grain legumes to the major legumes in-order to identify opportunities and challenges for their promotion. The objectives of the study were to (i) compare phenology, yield, ET and water productivity (WP) of selected underutilised grain legumes [bambara groundnut (*Vigna subterranea*) and cowpea (*Vigna unguiculata*)] and major grain legumes [groundnut (*Arachis hypogaea*) and dry bean (*Phaseolus vulgaris*)] across environments, and (ii) determine the species × environment interaction as well as yield stability analysis.

1.2 Materials and Methods

1.2.1 Site Description

Three sites with contrasting environments (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District), were selected in the KwaZulu-Natal Province of South Africa. Ukulinga Research Farm (29°37’S; 30°16’E; 750 meters above sea level) is classified as a subtropical climate with low risk of frost occurrence (Fig 1). Average annual rainfall is 694 mm which is received mainly during the summer months (mid-October to mid-February). During the summer months, average maximum temperatures are between 26°C and 28°C while minimum temperatures can be as low as 10°C. The soil was characterised as clay and was 0.4 m deep. Fountainhill Estate (29.447’S; 30.546’E; 1020 meters above sea level) is a farming estate that is classified as a subtropical highand climate with average annual rainfall of 905 mm (Fig 1). The highest rainfall (≈ 142 mm) is received in January while the driest month is June. Average annual temperatures at Fountainhill Estate are 20.4°C with February being the hottest month of the year and June the coldest month of the year. Fountainhill Estate has deep sandy soils. Umbumbulu Rural District lies 19 km from the Indian Ocean (29.984’S; 30.702’E; 593 meters above sea level) (Fig 1). It is located in a moist coastal hinterland region with the climate being sub-tropical popular for rainfall throughout the year. It is humid with annual rainfall between 900 to 1200 mm with most of it received during summer (October to March). Maximum temperatures range between 25 to 30°C with February being the hottest month while July is the coldest month. The soils at Umbumbulu are clay–loam.

Figure 1: Map of KwaZulu-Natal showing the location of the three study sites A - Ukulinga Research Farm, B – Fountainhill Estate, C – Umbumbulu Rural District. (Source: http://www.eishsa.co.za with some modifications).

1.2.2 Plant material

Groundnut variety Kwarts was sourced from Agricultural Research Council-Grain Crops Institute, Potchefstroom. Kwarts is a medium season variety taking up to 150 days to maturity. It has a tan testa (BFAP, 2012) and is popular for its wide adaptation in South Africa. Dry bean variety Ukulinga was sourced from McDonald seeds, Pietermaritzburg. Ukulinga is a medium to late maturing cultivar (120 days) with an upright bush growth habit. It was developed as an easy-to-harvest sugar bean and is well adapted to most dry-bean production areas. Cowpea variety mixed brown was sourced from Capstone seeds, Mooi River. Mixed brown is a medium season variety (120 days) and has a spreading growth habit. It is well adapted to various soil types. A bambara groundnut landrace was sourced from Jozini.

1.2.3 Experimental design

Groundnut, dry bean, cowpea and bambara groundnut were grown under rainfed conditions at three sites in KwaZulu-Natal, South Africa during the 2015/16 and 2016/17 summer season. At all sites, the experimental design was a completely randomised block design with three replications. At Ukulinga, cowpea was not included in the experimental design. At Umbumbulu, trials only established during the 2016/17 season. Plot size was 18.75 m^2. Plant population was 26 667 plants $hectare^{-1}$ for cowpea, 66 667 plants $hectare^{-1}$ for bambara groundnut and 88 889 plants $hectare^{-1}$ for dry bean and groundnut. Plant populations were based on the Department of Agriculture, Forestry and Fisheries (DAFF), recommended planting densities for rainfed conditions.

1.2.4 Trial management

During 2015/16, trials were planted on 17 November 2015 at Ukulinga and 4 December 2015 at Fountainhill. During 2016/17, trials were planted on 30 November, 14 December and 16 January 2016 at Umbumbulu, Fountainhill and Ukulinga, respectively. Prior to planting, soil samples were taken at each experimental site and submitted for fertility analysis. Results showed that at Ukulinga and Fountainhill, deficient N, P and K was 120, 20 and 0 kg ha^{-1}, respectively, while at Umbumbulu, deficient N, P and K was 120, 50 and 10 kg ha^{-1}, respectively. An organic fertiliser, Gromor accelerator (0.3% N, 0.15% P and 0.15% K), was applied at planting at a rate of 4000 kg ha^{-1} at all sites, to supply the deficient N, P and K needed to meet the nutrient requirements of the crops. Seeds were treated with an insecticide (Chlorpyrifos at the rate of 0.6 g of a.i /kg of seed) and a fungicide (Mancozeb at the rate of 0.0015 g a.i per ml per 1 kg of seed) before planting. For the duration of the trials, recommended best management practices (weeding, ridging and pest and disease control) for each crop were applied.

1.3 Data collection

1.3.1 Weather data

Daily weather data [maximum (Tmax) and minimum (Tmin) air temperature (°C), rainfall (mm) and reference evapotranspiration (ET_O) (mm)] were obtained from weather stations within 10 km radius from the trial sites. At Fountainhill and Umbumbulu, daily weather data was obtained from the South African Sugar Association (SASA) weather web portal (http://portal.sasa.org.za/weatherweb). At Ukulinga, daily weather data was obtained from an automatic weather station (AWS), which is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations. Number of rain days were defined as those days with rainfall > 2.5 mm (Nandargi and Mulye, 2012). Number of extremely hot days was recorded as number of days with Tmax above 33°C. Number of cold days was recorded as number of days with Tmin below 10°C. This was based on the upper and lower threshold temperatures for growth of grain legumes (Vara Prasad et al., 2002; Crauford et al., 2003)

1.3.2 Soil water content

Soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). The sensors of the PR2/6 profile probe are positioned to measure volumetric water content at six depths (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe). The effective depth of the soil at Ukulinga was determined as 0.40 m, hence only SWC measurements up to this depth were considered during analyses.

1.3.3 Phenology

The occurrence of phenological stages (emergence, flowering, podding, senescence and maturity) was done through visual observations. Emergence was recorded when the hypocotyl protruded 2 cm above the soil. A plot was defined to be flowering when at least 50% of the experimental plants had a fully opened flower. A plot was defined to be podding when at least one pod appeared on at least 50% of the experimental plants. Senescence was defined as when at least 10% of leaves on at least 50% of the experimental plants had senesced without forming new leaves. Maturity was when at least 50% of leaves on 50% of the experimental plants had senesced (Mabhaudhi and Modi, 2013). Phenology data was then converted to thermal time (growing degree days) using the equation by McMaster and Wilhelm (1997); where

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \qquad \textbf{Equation 1}$$

where; Tmax = maximum temperature (°C)

Tmin = minimum temperature (°C)

Tbase = base temperature for grain legumes (8°C).

If Tmax < Tbase then Tmax = Tbase, and if Tmin < Tbase, then Tmin = Tbase.

1.3.4 Yield and yield components

At harvest, six experimental plants were selected randomly from each plot. The plants were then air dried in a controlled environment at the UKZN Phytosanitary Unit until there were no changes in total biomass observed. Thereafter, yield components were determined (total biomass, pod number, pod mass, grain number and grain mass). In the case of dry bean and cowpea, total biomass referred to above ground biomass while for groundnut and bambara groundnut, total biomass referred to both below and above ground biomass.

Thereafter, harvest index (HI) was determined as:

$$HI = (\mathrm{Y_g/B}) \times 100 \qquad \textbf{Equation 2}$$

where: HI = harvest index (%), Y_g = economic yield based on grain yield (kg), and B = total biomass (groundnut and bambara groundnut)/ above ground biomass (dry bean) (kg).

1.3.5 Determination of ET

Evapotranspiration (ET) for each treatment was calculated as the residual of a soil water balance (Allen et al., 1998):

$$\mathrm{ET = P + I - D - R - \Delta SWC} \qquad \textbf{Equation 3}$$

where: ET = evapotranspiration (mm) = water use (mm),

P = precipitation (mm),

I = irrigation (mm),

D = drainage (mm),

R = runoff (mm), and

ΔSWC = changes in soil water content (mm).

Drainage was considered as negligible. At Ukulinga there was an impeding layer at 0.4 m which restricted downward movement of water beyond the root zone. At Fountainhill and Umbumbulu drainage was considered negligible based on Dancette and Hall (1979) where in semi-arid environments drainage is negligible if the profile is not periodically saturated to drain excess water. Runoff (R) was not quantified during the trials. However, to account for its effect the United States Department of Agriculture - Soil Conservation Service (USDA-SCS) procedure (USDA-SCS, 1967) was used to estimate the monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to runoff. The soil water balance was therefore simplified to;

$$\mathrm{ET = ER \pm \Delta SWC} \qquad \textbf{Equation 4}$$

where: ET = evapotranspiration (mm) = water use (mm), ER = effective rainfall (mm),

ΔSWC = changes in soil water content (mm).

Values of ET in mm (depth) were then converted to m^3 (volume) using the formula;

$$\text{Volume } (m^3) = \text{Area } (m^2) \times \text{Depth } (m) \qquad \textbf{Equation 5}$$

1.3.6 Determination of ET

Water Productivity was then calculated as;

$$WP = Y_a / ET \qquad \textbf{Equation 6}$$

where: WP is water productivity (kg m^{-3}), Y_a is the grain yield (kg) and ET is the actual evapotranspiration (m^3).

1.3.7 Data Analysis

Data for each site and season were subjected to Analysis of Variance (ANOVA) in GenStat® 18th Edition (VSN International, UK) following a Bartlett's test for homogenity of equal variances. Thereafter, an unbalanced threeway ANOVA model was conducted for grain yield. Mean grain yields of species for the combinations of the three sites and two seasons, treated as five environments, were computed to generate a species and environment two-way table data for the biplot analysis. The biplot analysis was done using GGE biplot (Yan and Tinker, 2006) in GenStat® 18th Edition (VSN International, UK), to generate graphs showing (i) "which-won-where" pattern, and (ii) ranking of species on the basis of mean yield and stability.

1.4 Results

1.4.1 Weather data

The highest seasonal rainfall were received at Fountainhill and Umbumbulu during 2015/16 and 2016/17, respectively (583 mm and 595 mm, respectively) (Table 1). This was distributed over 37 and 40 days, respectively, implying avarage rainfall of ≈ 15 mm per rain day. During 2016/17, Ukulinga received ≈ 40% of rainfall received at Umbumbulu. Although Umbumbulu received the highest rainfall (595 mm), ET_o was higher creating a deficit of 5 mm (Table 1). This was common across sites and seasons with the highest rainfall deficit (180 mm) being observed at Ukulinga during 2016/17 season. An expeception was Fountainhill during 2015/16 where rainfall exceeded ET_o by 61 mm. For seasonal average Tmin there was a difference of

4°C between the highest and lowest seasonal average Tmin (Table 1). There was a 7°C difference between the highest Tmin (Ukulinga during 2016/17) and the lowest Tmin (Fountainhill during both seasons). The highest number of cold days were observed at Fountainhill during 2016/17 (four to eight times more than Ukulinga and Umbumbulu) (Table 1).

Table 1: Observed weather characteristics at the three selected sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) during the two seasons 2015/16 and 2016/17.

	Fountainhill		**Ukulinga**		**Umbumbulu**	
Season	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
Total seasonal Rainfall (mm)	583	395	445	235	–	595
Number of rain days	37	27	41	20	–	40
Total seasonal ET_o (mm)	522	526	517	415	–	600
Seasonal average Tmax (°C)	27	27	29	27	–	29
Highest Tmax (°C)	39	39	41	38	–	42
Number of extremely hot days	13	13	21	21	–	37
Seasonal average Tmin (°C)	15	13	16	15	–	17
Lowest Tmin (°C)	3	3	10	7	–	6
Number of cold days	–	26	4	8	–	4
Frost occurence	No	No	No	No	No	No
Hail storm occurence	No	No	No	No	Yes	No

1.4.2 Timing of key phenological stages

Results of timing of phenological events were significantly different ($P < 0.05$) among the crops. This was consistent across all sites and seasons (Table 2). Bambara groundnut had a tendency to emerge late across all sites and seasons (252 – 378 growing degree days) (Table 2). For dry bean, slow emergence was only observed at Fountaihill where it took twice as much time to emerge compared to the other sites. Consistent across sites and seasons, bambara groundnut flowered late (> 778 growing degree days), one to two weeks after the other crops had already started podding (Table 2). During 2015/16, a shorter flowering duration was observed (250 – 360 growing degree days) compared to 2016/17 season (344 – 384 growing degree days). Dry bean had the shortest flowering duration (< 316 growing degree days DAP) while groundnut had the longest flowering duration (Table 2). Comparing the crops, dry bean was early maturing (< 1 677 growing degree days) while groundnut and bambara groundnut were late maturing (> 1 700 growing degree days). However for bambara groundnut it was observed that while it matured ≈ 1 700 growing degree days DAP at Fountainhill and Ukulinga during 2015/16 and 2016/17, respectively, at Umbumbulu it took more time (2 285 gowing degree days) (Table 2).

1.4.3 Yield components

Results of yield and yield components showed that most measured variables were significantly different ($P < 0.05$) at all sites and across all seasons (Table 3). This was with the exception of biomass and HI at Fountainhill during 2015/16, pod yield at Fountainhill during 2016/17 and biomass at Ukulinga during 2016/17. At Fountainhill, it was observed that one of the major grain legumes (groundnut) and an underutilised grain legumes (bambara groundnut) responded well to the environment. The nut crops (bambara groundnut and groundnut) had the highest biomass at Fountainhill where the soil was sandy. During 2016, bambara groundnut had the highest biomass (6 352 kg ha^{-1}), while during 2016/17 groundnut had the highest biomass (6 855 kg ha^{-1}) (Table 3). At Ukulinga, the major grain legumes (groundnut and dry bean) had the highest biomass during both seasons. The highest biomass across all crops, sites and seasons (9 654 kg ha^{-1}) was observed for groundnut at Ukulinga during 2015/16. The crops responded negatively to the low rainfall at Ukulinga during 2016/17, with the crops attaining their lowest biomass compared to the other seasons and sites. At Umbumbulu trends were similar to Fountainhill — the nut crops (groundnut and bambara groundnut) had the highest biomass (6 669 and 3 344 kg ha^{-1}, respectively) compared to the other crops (Table 3). Although bambara groundnut had the second highest biomass at Umbumbulu this was ≈ 50% of groundnut biomass.

At Fountaihill, similar to results of biomass, the nut crops (bambara groundnut and groundnut) had superior pod yields. High pod number translated to high pod yield at Fountainhill during both seasons. The high pod number for bambara groundnut (77) was translated to high pod yield (3 403 kg ha^{-1}) during 2015/16. During 2016/17 it was groundnut with the highest pod number (62) and pod yield (3 537 kg ha^{-1}) (Table 3). At Ukulinga, the major legumes (groundnut and dry bean) performed better than bambara groundnut — bambara groundnut had the lowest pod yield during both seasons (< 1 451 kg ha^{-1}). At Umbumbulu, groundnut had the highest pod yield (2 884 kg ha^{-1}) which was ≈ seven times more that of dry bean (406 kg ha^{-1}). With respect to grain number, cowpea had the highest number of grains across all sites (273 – 295). High grain number in cowpea did not translate to high grain yield. At Fountainhill, cowpea had the lowest grain yield (1 241 kg ha^{-1} during 2015/16 and 1 011 kg ha^{-1} during 2016/17) (Table 3). Bambara groundnut had the highest grain yield at Fountainhill during the 2015/16 (1 978 kg ha^{-1}) while it had the lowest grain yield (1 099 kg ha^{-1}) at Ukulinga during the same season. During 2016/17, groundnut had the highest grain yield at Fountainhill and Ubumbumbulu (2 387 and 1 213 kg ha^{-1}, respectively), but the lowest grain yield at Ukulinga (262 kg ha^{-1}). For dry bean, the highest grain yield was observed at Ukulinga during 2015/16 (1 967 kg ha^{-1}) while the lowest yield was observed at Umbumbulu (282 kg ha^{-1}) (Table 3).

With respect to HI, it was observed that across all sites and seasons dry bean had a higher HI compared to the other crops. The highest HI of dry bean (56%) was observed at Fountainhill during 2016/17 (Table 3). This was ≈ 300% higher than HI for bambara groundnut at the same site during the same season. A consistently low HI was observed for bambara groundnut across all sites and seasons (< 30%).

1.4.4 Evapotranspiration and WP

For groundnut, ET ranged from 234 mm at Umbumbumbu to 349 mm at Fountainhill during 2015/16 season. Water productivity fluctuated from 0.98 kg m^{-3} at Ukulinga to as low as 0.12 kg m^{-3}, this was consistent with observed low grain yield (Fig 2). For bambara groundnut, ET ranged from 232 mm at Ukukinga during 2016/17 to 437 mm at Fountainhill during 2016/17. Water productivity ranged from 0.16 kg m^{-3} at Ukulinga during 2016/17 to 0.51 kg m^{-3} at Fountainhill during 2016/17 (Fig 2). The low WP observed at Ukulinga during 2016/17 was consistent with observed low grain yield (267 kg ha^{-1}) (Fig 2 and Table 3). Dry bean was early maturing and had the lowest ET (208 – 313 mm). Similar to groundnut and bambara groundnut, WP for dry bean showed much fluctation consistent with observed yield fluctuation (0.13 kg m^{-3} at Umbumbulu to 0.84 kg m^{-3} at Ukulinga during 2015/16) (Fig 2). Cowpea ET ranged from 273 – 334 mm and similar to grain yield, although it was not the highest WP, it did not show much fluctuation (0.28 – 0.38 kg m^{-3}) compared to bambara groundnut, dry bean and groundnut.

Table 2: Timing of key phenological stages of four grain legume species (dry bean, groundnut, bambara groundnut and cowpea) grown at three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) over two seasons (2015/16 and 2016/17).

Site	**Crop**	**2015/16**						**2016/17**					
		[a]TTE	[b]TTF	[c]DOF	[d]TTP	[e]TTS	[f]TTM	[a]TTE	[b]TTF	[c]DOF	[d]TTP	[e]TTS	[f]TTM
		Growing degree days											
Fountainhill	Dry bean	349a	623b	196a	778b	1263b	1486	349a	750b	273b	850	1155b	1384c
	Groundnut	320b	414c	360a	565c	1468a	1699	232a	550c	468a	750	1603a	1763a
	Bambara Groundnut	378a	778aa	360a	902a	1484a	1699	376a	973a	384a	1022	1603a	1708a
	Cowpea	292b	539abb	365a	778b	1185b	1486	297a	716b	464a	850	1399ab	1622b
	l.s.d *(P=0.05)*	64	64	136	72	128	–	58	73	51		198	90.5
Ukulinga	Dry bean	102b	724b	206a	812	1365b	1677	119a	642ab	244b	773bb	1383b	1582b
	Groundnut	117.4b	386c	216a	601	1592ab	1773	205a	376c	417a	670bb	1737a	1965a
	Bambara Groundnut	211a	842a	250a	1081	1705b	1921	269a	862a	347ab	1031aa	1399b	1743a
	l.s.d *(P=0.05)*	23	–	91	–	207		124	363	131	137	108	132
Umbumbulu	Dry bean	–	–	–	–	–	–	184	770bb	316c	873ab	1246c	1464c
	Groundnut	–	–	–	–	–	–	184	602cc	413a	707b	1801b	2086bc
	Bambara Groundnut	–	–	–	–	–	–	252	938aa	344b	1092a	1917a	2285a
	Cowpea	–	–	–	–	–	–	104	707abb	414a	867ab	1652b	1937b
	l.s.d *(P=0.05)*	–	–	–	–	–	–	-	80.6	-	179	45	144.6

[a]TTE = Time to emergence; [b]TTF = Time to flowering; [c]DOF= Duration of flowering; [d]TTP = Time to podding; [e]TTS = Time to senescence; [f]TTM = Time to maturity. Means with different letters are significantly different at $P < 0.05$. Since the unit of time that was used to collect data was days, only discrete values are presented in this table.

Table 3: Yield and yield parameters (total biomass, pod number, pod mass, grain number, grain mass and harvest index) of four grain legume species (dry bean, groundnut, bambara groundnut and cowpea) grown at three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) over two seasons (2015/16 and 2016/17).

		2015/16						2016/17					
		Biomass	**Pod number**	**Pod yield**	**Grain number**	**Grain Yield**	**HI**	**Biomass**	**Pod number**	**Pod yield**	**Grain number**	**Grain Yield**	**HI**
Site	**Crop**	kg ha^{-1}	plant $^{-1}$	kg ha^{-1}	plant $^{-1}$	kg ha^{-1}	%	kg ha^{-1}	plant $^{-1}$	kg ha^{-1}	plant $^{-1}$	kg ha^{-1}	%
Fountainhill	Dry bean	4 496a	17c	2 235ab	45b	1 456ab	32.9a	2 219b	11b	1 787a	30b	1 302a	56.7a
	Groundnut	5 789a	53b	2 883ab	55b	1 594ab	27.0a	6 855a	62a	3 537a	78b	2 387a	34.1b
	Bambara Groundnut	6 352a	77a	3 403a	70b	1 978a	30.6a	5 156a	40ab	2 303a	38b	1 359a	19.8b
	Cowpea	4 401a	25c	1 866b	229a	1 241b	29.1a	2 394b	27ab	1 343a	295a	1 011a	43.7a
	l.s.d $_{(P=0.05)}$	2 306	23	1 335	72	786	6.23	3 424	43	2 596	89	1 539	22.2
Ukulinga	Dry bean	5 284b	22b	2 890b	50b	1 967ab	37a	2 543a	13a	1 409a	29a	1 081a	42.6a
	Groundnut	9 654a	69a	4 568a	100a	2 272a	29ab	2 148a	17a	537b	17b	267b	12.7b
	Bambara Groundnut	5 000b	44b	1 651b	38b	1 099b	21b	1 346a	12a	447b	18b	292b	18.8ab
	l.s.d $_{(P=0.05)}$	2 020	23	1 279	33	964	8	1 167	12	569	7	546	27.9
Umbumbulu	Dry bean	–	–	–	–	–	–	652c	4b	406b	9b	282c	43.2a
	Groundnut	–	–	–	–	–	–	6 669a	34a	2 284a	42b	1 213a	18.8b
	Bambara Groundnut	–	–	–	–	–	–	3 344a	27a	1 562a	24b	725b	22.2b
	Cowpea	–	–	–	–	–	–	3 315b	26a	1 555a	273a	953ab	28.4b
	l.s.d $_{(P=0.05)}$	–	–	–	–	–	–	2 704	13	832.6	58	465	9.8

Means with different letters are significantly different at $P < 0.05$. Since pods and grain were counted as whole numbers, only discreet values of pod and grain number are presented.

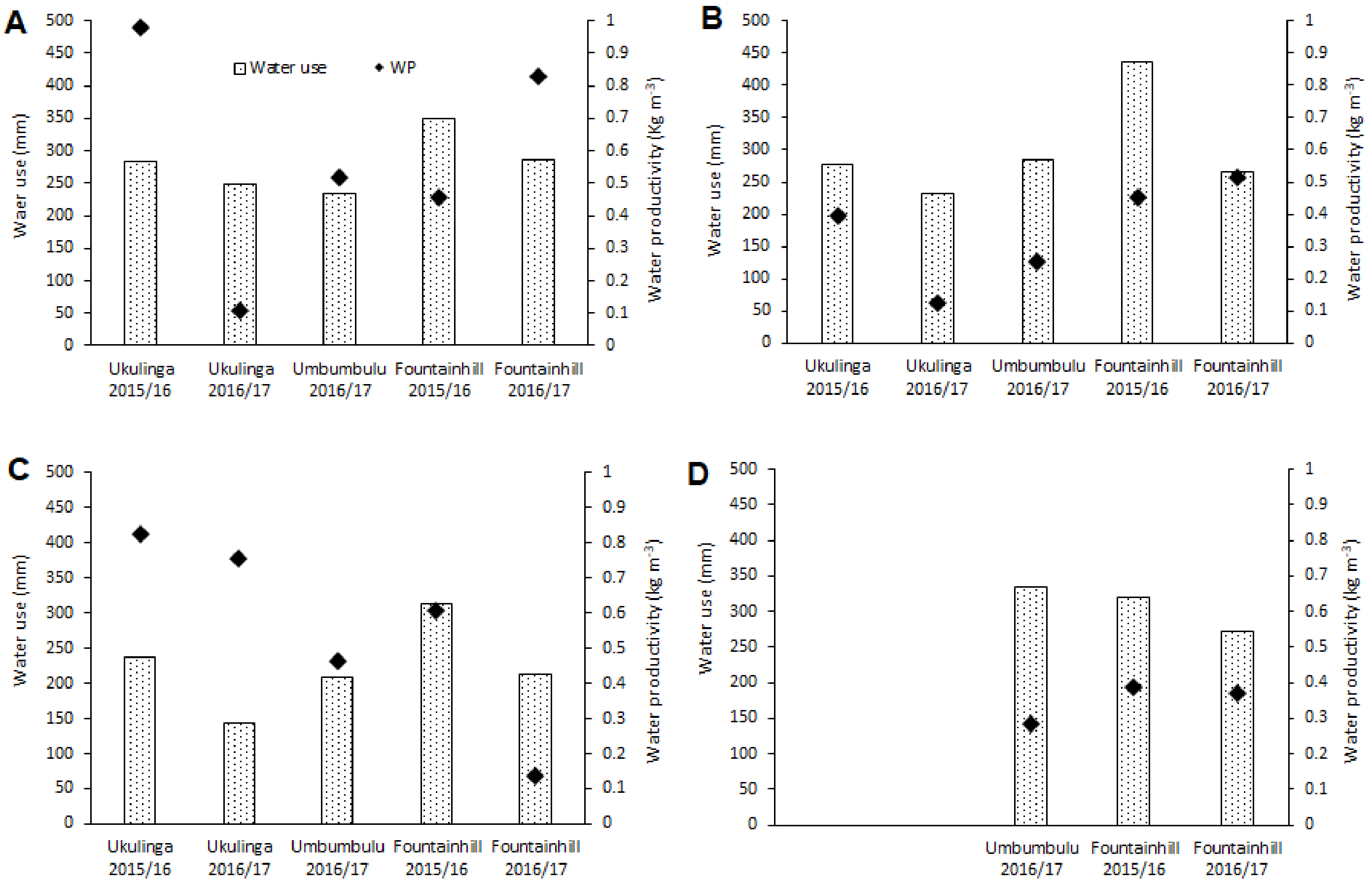

Figure 2: Water use (mm) and water productivity (kg m^{-3}) of four grain legume species (A = groundnut, B = bambara groundnut, C = dry bean and D = cowpea) grown at three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) over two seasons (2015/16 and 2016/17).

1.4.4 Species grain yield × environment

Analysis of variance showed highly significant differences ($P < 0.001$) for site, season and the interaction between site and season. The interaction between site and season and season on its own were the major cause of variation in yield data. This supports the need for species × environment analysis and confirms the results of the Bartlett's test that seasons were not homogenous. Species on their own and the interaction between site and species was significantly different ($P < 0.05$). The three way interaction between site, species and season was also significantly different ($P < 0.05$). No significant differences ($P > 0.05$) were observed for the interaction between season and species. The interaction between season and species only accounted for 0.9% of the variation of grain yield data.

The 'which won where'pattern biplot showed that of the four polygon sectors that represent environments, the five environments only fell into two sectors, forming two different mega environmets (Fig 3). The first mega environment consisted of Ukulinga 2015/16, Umbumbulu 2016/17 and Fountainhill 2015/16 and 2016/17. Ukulinga 2016/17 where lowest rainfall and highest rainfall deficit to ET_o was observed formed the second environment on its own. At each of the mega environments, it was a major legume that was the winning speces. In the first mega environment groundnut was the winning species implying that groundnut performed best at four out of the five environments. In the second mega environment dry bean was the winning species (Fig 3). The underutilised grain legumes (bambara groundnut and cowpea) did not show any grain yield superiority at any of the environments.

The arrow shown on the axis of the (average-environment coordination) AEC in Figure 4 points in the direction of higher mean performance of the species. Species are ranked according to mean performance. Groundnut had the highest mean yield while dry bean mean yield was similar to the grand mean. The underutilised grain legumes (bambara groundnut and cowpea) had mean yields that were below the grand mean and cowpea was the lowest yielding species. The major legumes out-perfomrmed the underutilised grain legumes with respect to yield quantity. On the same figure (4), the projection of species markers onto the AEC approximates the stability of species grain yield. The stability ranking of the species is based on the increasing absolute difference between genotype marker and AEC axis in either direction. In this regard, a minor grain legume (cowpea) showed the highest yield stability. Although cowpea had low mean grain yields, it did not show much variability compared to other crop species, hence high yield stability (Fig 4). This was followed by groundnut. Dry bean was the least stable and showed greater variability which was as a result of high yield at Ukulinga and poor yield at Umbumbulu during 2016/17.

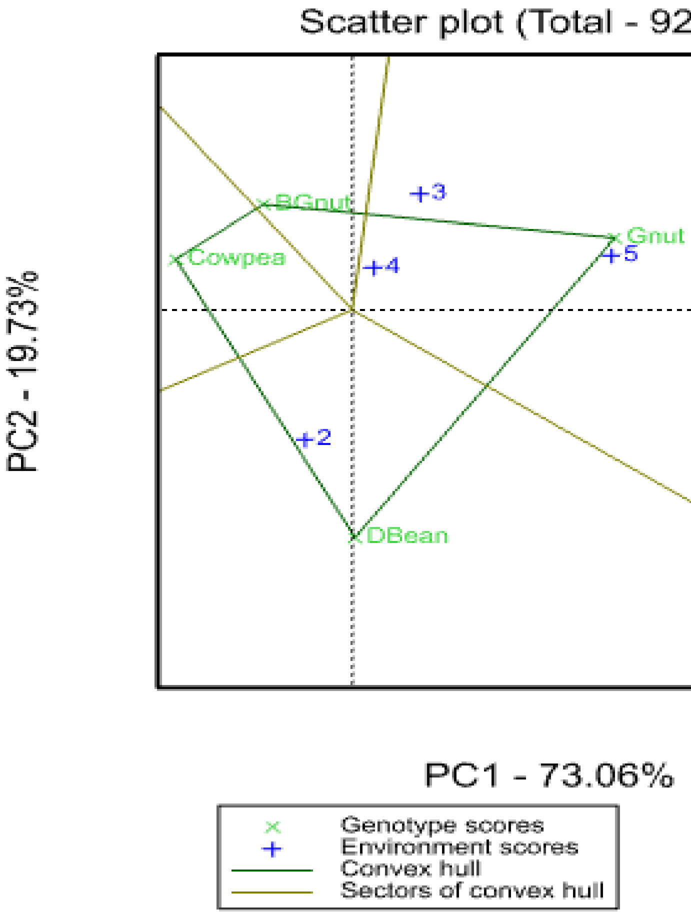

Figure 3: GGE biplot based on environment showing "which-won-where". The environments are indicated as 1 for Ukulinga 2015/16, 2 for Ukulinga 2016/17, 3 for Umbumbulu 2016/17, 4 for Fountainhill 2015/16 and 5 for Fountainhill 2016/17. Species are denoted by Gnut = groundnut, BGnut = bambara groundnut, DBean = dry bean and cowpea.

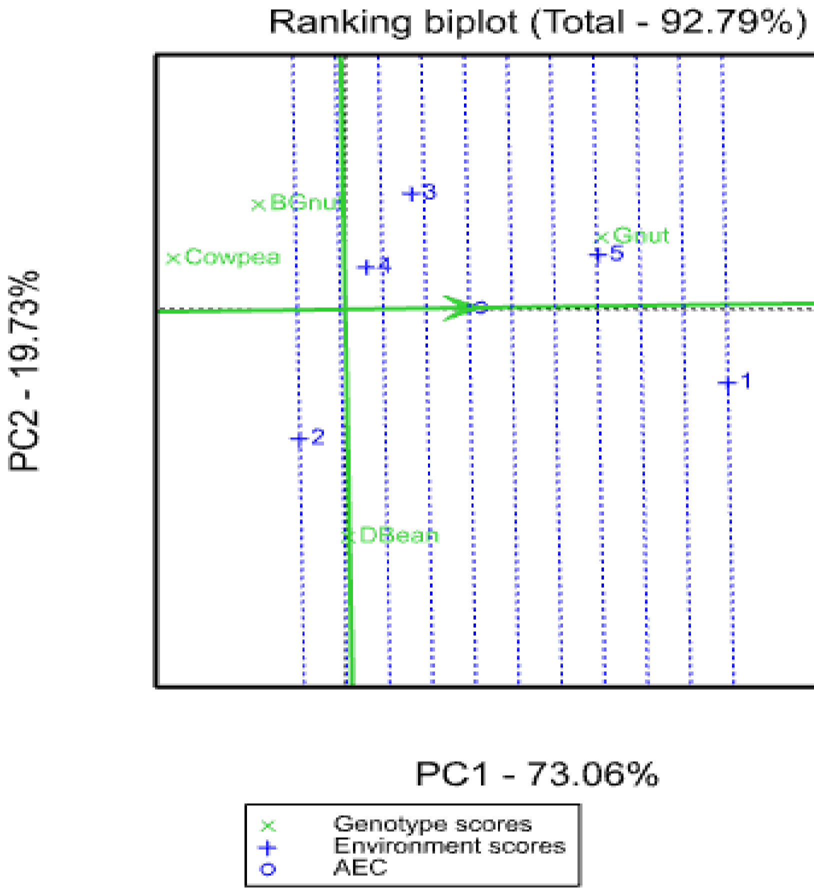

Figure 4: The “mean vs. stability” GGE biplot. An ideal cultivar should be at the centre of average environment coordinate (AEC)s. The environments are indicated as 1 for Ukulinga 2015/16, 2 for Ukulinga 2016/17, 3 for Umbumbulu 2016/17, 4 for Fountainhill 2015/16 and 5 for Fountainhill 2016/17. Species are denoted by Gnut = groundnut, BGnut = bambara groundnut, DBean = dry bean and cowpea.

1.5 Discussion

The objectives of the study were to (i) determine phenology, yield, ET and (WP) of selected underutilised grain legumes and major grain legumes across environments, and (ii) determine the species × environment interaction as well as yield stability analysis. The grain legumes under study responded differently to the environments. This influenced the crops' development, yield, ET and WP. With respect to time to emergence, the crops emerged relatively slower at Fountainhill during both seasons, compared to the other sites. This suggests that the sandy soils at Fountainhill had a negative effect on time to emergence. This was consistent with findings by Lima et al. (2010) and Reichert et al. (2015) who observed poor emergence in sandy soil. Sandy soils have a poor water holding capacity, limiting water availability to the germinating seed. Bambara groundnut was consistently the slowest to emerge regardless of site and season. Slow emergence of bambara groundnut has been reported by several authors (Makanda et al., 2008; Legwaila et al., 2013; Mabhaudhi and Modi, 2013). Slow establishment and poor crop stand decrease yield and increase unproductive ET through soil evaporation (Mabhaudhi and Modi, 2013). There is need for crop improvement of bambara groundnut to reduce time to establishment and to increase plant stand. This will ultimately improve yield.

Soil type has been shown to influence yield of crops. Crops respond differently to soil type (Barraclough and Leigh, 1984; Tolk et al., 1999). Bambara groundnut yielded better at Fountainhill where the soil was sandy. At Fountainhill, bambara groundnut yield was similar to groundnut. Despite the sandy soil negatively affecting crop emergence, it was a favourable attribute for the two crops as they bear fruit below ground. Sandy soil has a loose structure and large pores allowing for growth of pods. Moreso, when sandy soils are dry they form thin cracks that are loose (Tester, 1990; Brady and Weil, 2010). This is a favourable attribute, especially in the semi and arid tropics were rainfall is erratic and soil is exposed to long dry periods. Although clay soil has a good water holding capacity it expands when wet and conversely shrink when exposed to long dry periods (Brady and Weil, 2010). When clay soil shrinks it forms cracks that may not be favourable for groundnut and bambara groundnut as it inhibits pod growth. This could be the reason for the observed poor pod yield of groundnut and bambara groundnut at Ukulinga during 2016/17 season where rainfall was lowest. When soil inhibits pod growth it further limits harvest index of bambara groundnut that is low (20 – 30%) compared to other grain legumes (30 – 60%). Low harvest index has negative implications on grain yield and reduces WP of a crop.

High ET_o, rainfall and late maturity of plants are characteristics associated with high ET in plants (Allen et al., 1998). The highest ET_o (600 mm) and rainfall (595 mm) was observed at Umbumbulu during 2016/17. At the same site, the season was long with bambara groundnut taking up to 152 days to mature. It would be expected that the highest crop ET would be observed at Umbumbulu. However, this was not the case — the highest ET was not observed at Umbumbulu for all the crops. It was also observed that Umbumbulu had the highest number of extremely hot days (37) compared to the other environments that had less than 21 extremely hot days. The crops could have adjusted to the high temperatures through leaf rolling, changes in leaf orientation and stomatal closure to maintain homeostasis (Hasanuzzaman et al., 2013). This resulted in conserved ET and could be the reason Umbumbulu did not have the highest ET. Dry bean was the least performing species at Umbumbulu. This implies that dry bean was most sensitive crop to hot days observed at Umbumbulu, compared to the other crops (cowpea, groundnut and bambara groundnut). This supports the findings by several authors that dry bean was sensitive to heat stress especially during flowering which led to significant yield loss (Monteroso and Wien, 1990; Porch and Jahn, 2001; Vara Prasad et al., 2002).

While dry bean was sensitive to the number of hot days at Umbumbulu, it was more tolerant to the low rainfall at Ukulinga during 2016/17, compared to groundnut and bambara groundnut. This could be attributed to the determinate growth habit of the dry bean cultivar used in the study. The early establishment and short flowering duration observed could have worked favourably for dry bean as it was able to accumulate biomass early and partition it to yield before the onset of dry period. This was supported by the high harvest index observed for dry bean at Ukulinga during 2016/17. Groundnut was the highest performing species. It was higher yielding compared to the other crops under study. However, at Fountainhill, bambara groundnut yield was similar to groundnut. A bambara groundnut landrace was used in the study while groundnut was a bred cultivar. This implies that bambara groundnut could have the same yield potential as groundnut. Breeding efforts focussing on G × E interaction and stability of bambara groundnut still need to be addressed for the crop to achieve the same broad based high yield across environments as groundnut.

Crop breeding has mainly focused on increasing yield under specific environments, mainly targeted for commercial agriculture. Often these high yielding cultivars fail when grown under different environments and in times of extreme climate events such as drought (Calderini and Slafer, 1998; Ceccarelli et al., 1991). This was observed for the major grain legumes (groundnut and dry bean). Under subsistence agriculture where grain is the main source of livelihood, when crop yield fails drastically this leads to famine. Under these circumstances stable crop species are more important compared to high yielding unstable species (Abbo et al., 2010). Cowpea would be an ideal crop under these circumstances as it exhibited the highest yield stability across environments. Cowpea also had a more stable WP, but it was lower compared to the major grain legumes. Lower WP in cowpea was as a result of lower yield compared to the major grain legumes. Improving WP in cowpea should focus on increasing yield of the crop.

In the context of improving WP in semi- and arid environments, the main goal is to increase yield from the current ET. In situations where crop yield is significantly less than its potential there is prospects to improve WP without increase in ET (Molden et al., 2010). In situations where crop yields are almost near their potential, any increase in yield will be accompanied by increase in ET (Molden et al., 2010). More gains in WP will be achieved through improving yield that is far from its potential through breeding and agronomic improvements. This study showed that bambara groundnut has the potential to yield as high as groundnut under ideal environments. Improving yield of bambara groundnut so that it reaches its potential may lead to gains in WP in semi- and arid environments.

1.6 Conclusion

The hypothesis that underutilised grain legumes could be more adapted across environments in the semi- and arid tropics was not entirely true. The major legumes (groundnut and dry bean) were higher yielding compared to the underutilised grain legumes (bambara groundnut and cowpea). Groundnut performed well across all environments except under low rainfall. Dry bean performed equally well and had the highest yield under low rainfall. This was associated with high harvest index in dry bean. However, its performance was constrained in hot environments indicating sensitivity to heat stress. Bambara groundnut performed well in sandy compared to clayey soils. Under sandy soil, bambara groundnut biomass and grain yield was similar to that of groundnut. Although, cowpea was the lowest yielding species, it had a more stable grain yield and WP across environments. An understanding of G × E interaction for grain legumes could translate to improved yields and productivity through identification of best environments different crops. Investments in improving yield of underutilised grain legumes and yield stability of major legumes may lead to greater adoption of grain legumes in rural areas. Future breeding strategies should consider (i) improving yield stability and tolerance to extreme weather events, and (ii) inclusion of underutilised grain legumes in breeding programs.

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CHAPTER 5

NUTRIENT CONTENT AND NUTRITIONAL WATER PRODUCTIVITY OF SELECTED GRAIN LEGUMES IN RESPONSE TO PRODUCTION ENVIRONMENT

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Abstract: There is a need to incorporate nutrition into aspects of crop and water productivity to tackle food and nutrition insecurity (FNS). The study determined the nutritional water productivity (NWP) of selected major (groundnut, dry bean) and indigenous (bambara groundnut and cowpea) grain legumes in response to water regimes and environments. Field trials were conducted during 2015/16 and 2016/17 at three sites in KwaZulu-Natal, South Africa (Ukulinga, Fountainhill and Umbumbulu). Yield and evapotranspiration (ET) data were collected. Grain was analysed for protein, fat, Ca, Fe and Zn nutrient content (NC). Yield, ET and NC were then used to compute NWP. Overall, the major legumes performed better than the indigenous grain legumes. Groundnut had the highest NWP_{fat}. Groundnut and dry bean had the highest $NWP_{protein}$. For $NWP_{Fe,\ Zn\ and\ Ca,}$ dry bean and cowpea were more productive. Yield instability caused fluctuations in NWP. Water treatments were not significant ($p > 0.05$). While there is scope to improve NWP under rainfed conditions, a lack of crop improvement currently limits the potential of indigenous grain legumes. This provides an initial insight on the nutrient content and NWP of a limited number of selected grain legumes in response to the production environment. There is a need for follow-up research to include cowpea data. Future studies should provide more experimental data and explore effects of additional factors such as management practices (fertiliser levels and plant density), climate and edaphic factors on nutrient content and NWP of crops.

Keywords: bambara groundnut; cowpea; dry bean; evapotranspiration; food and nutrition insecurity; groundnut; yield

1. Introduction

Two billion people suffer from micronutrient deficiency, with nearly one billion being calorie deficient (International Food Policy Research Institute (IFPRI), 2016). There is a gap between food supply and nutritional requirements, which has been attributed to a lack of nutritional considerations in crop production (Schönfeldt et al., 2017). There is a need for a paradigm shift in current food production to consider nutrition outcomes (Mabhaudhi et al., 2016). Increasing food production and productivity should be tied to increasing nutrient density. In this regard, agriculture could simultaneously address the challenge of increasing food production and improving nutrition under limited resource availability. However, there are often challenges to linking disciplines as there are often no appropriate metrics for evaluating such linkages. In the case of quantifying the water-food-nutrition nexus, nutritional water productivity (NWP) has been proposed as a useful metric (Renault and Wallender, 2000).

Nutritional water productivity is a measure of yield and nutrition outcome per unit of water consumed and would be applicable for sustainable food production given the limited water resources and modified diets (Renault and Wallender, 2000; SIWI and IWMI, 2004) . To date, increasing food production under water scarcity has been evaluated using different metrics such as “water use efficiency” and “water productivity” (Descheemaeker et al., 2013; Molden et al., 2010, 2003; Stanhill, 1986; Steduto, 1996). On the other hand, nutritionists have quantified nutritional content of different foodstuffs and suggested diets for improving nutritional status of people. These efforts have been parallel and needed to be merged to address the challenge of producing more nutritious food under water scarcity. Nutritional water productivity would be a useful metric in the semi- and arid tropics (South Asia and sub-Saharan Africa) where water scarcity and food and nutrition insecurity are prevalent (Mabhaudhi et al., 2016).

The high prevalence of food and nutrition insecurity has been attributed to dominance of starch in diets leading to poor dietary diversity. Diets lack in protein, micro nutrients and minerals (Abrahams et al., 2011; Baker et al., 1996; Bourne et al., 2002; Diskin, 1994). This leads to various forms of malnutrition, including but not limited to, stunting, wasting and underweight in children under five, anaemia in women of the reproductive age, obesity and type 2 diabetes (IFPRI, 2016). Dietary diversity has been recommended to alleviate malnutrition. Dietary diversity is defined as the number of different foods or food groups consumed over a given reference period (Ruel, 2003). Increasing the variety of foods across and within food groups ensures adequate intake of essential nutrients to promote good health. Grain legumes are being promoted in the semi- and arid tropics, as part of dietary diversity efforts. They are rich in proteins and some micronutrients (Duranti and Gius, 1997; Iqbal et al., 2006; Seena et al., 2006), hence have the potential to alleviate malnutrition. The nutritional properties of grain legumes have been associated with reduction of environmental enteric dysfunction (EED) (Borresen et al., 2017)—an incompletely defined syndrome of inflammation, reduced absorptive capacity, and reduced barrier function in the small intestine which is common among the rural poor in the semi- and arid tropics (Crane et al., 2015). Crop diversification through inclusion of indigenous grain legumes in food and nutrition agendas has been proposed by several authors (Chibarabada et al., 2017; Chivenge et al., 2015; Foyer et al., 2016; Mabhaudhi et al., 2016). A study on nutrient content and NWP of indigenous and exotic vegetables observed that crops differed in their nutrient content and NWP (Nyathi et al., 2016.). For some micro nutrients, indigenous vegetables were more nutrient dense compared to the reference exotic vegetable swiss chard (*Beta vulgaris*).

In the semi- and arid tropics, water is one of the main limiting factors in agriculture. Yield of grain legumes has been observed to decrease with decreasing water availability (Daryanto et al., 2015; Farooq et al., 2017; Pandey et al., 1984). Grain legumes have also been associated with yield instability across environments. There is not much information on how water availability and different environments affect nutritional content of grain legumes. Moreover, there is need to link yield, water use and nutritional content of grain legumes to establish the best yielding crops that use less water and are nutritionally dense. This should include indigenous grain legumes as they form part of crop diversification efforts. This information will be useful for promotion of grain legumes across different environments. It is hypothesised that nutrient content and NWP of crops will not vary with varying water availability and across environments. The aim of the study was therefore to determine the effect of production environment on NWP of selected indigenous and major grain legumes that share the same ecological niche and are usually consumed as whole grains by the rural population. The specific objectives were to determine nutrient content and NWP of selected indigenous [bambara groundnut (*Vigna subterranea*) and cowpea (*Vigna unguiculata*)] and major grain legumes [groundnut (*Arachis hypogaea*) and dry bean (*Phaseolus vulgaris*)] in response to (i) water regimes and (ii) environments.

2. Materials and Methods

2.1. Plant Material

Two major grain legumes that are recognised internationally (groundnut and dry bean) and two African indigenous grain legumes that are being promoted as healthy alternatives (bambara groundnut and cowpea) were selected for the study (Figure 1). Groundnut has high oil content and is usually consumed as a snack or processed to peanut butter or groundnut oil. Bambara groundnut, cowpea and dry bean, are normally harvested as dry grain and consumed after boiling them. Bambara groundnut and groundnut, form pods below ground while dry bean and cowpea form pods above ground. For the study, popular South African varieties of groundnut (Kwarts), dry bean (Ukulinga) and cowpea (mixed brown) were used for the study. For bambara groundnut, a mixed colour landrace from Jozini, South Africa was used. Kwarts is a variety suitable for warm dry areas. Ukulinga is a high yielding variety of dry bean that is well adapted to most dry bean producing areas. Mixed brown is a drought tolerant variety that is well adapted to most soils. There was no information on the bambara groundnut landrace.

2.2. Site Description

Three sites (one on-station and two on-farm) were selected from KwaZulu-Natal Province, South Africa (Table 1). Ukulinga, which was the on-station farm, is a Research Farm, belonging to the University of KwaZulu-Natal. Ukulinga has access to irrigation. Umbumbulu and Fountanhill were on farm trials and did not have access to irrigation. Umbumbulu is a rural district in the eThekwini district of KwaZulu-Natal. Fountainhill is an Estate 2 km outside of Wartburg, KwaZulu-Natal.

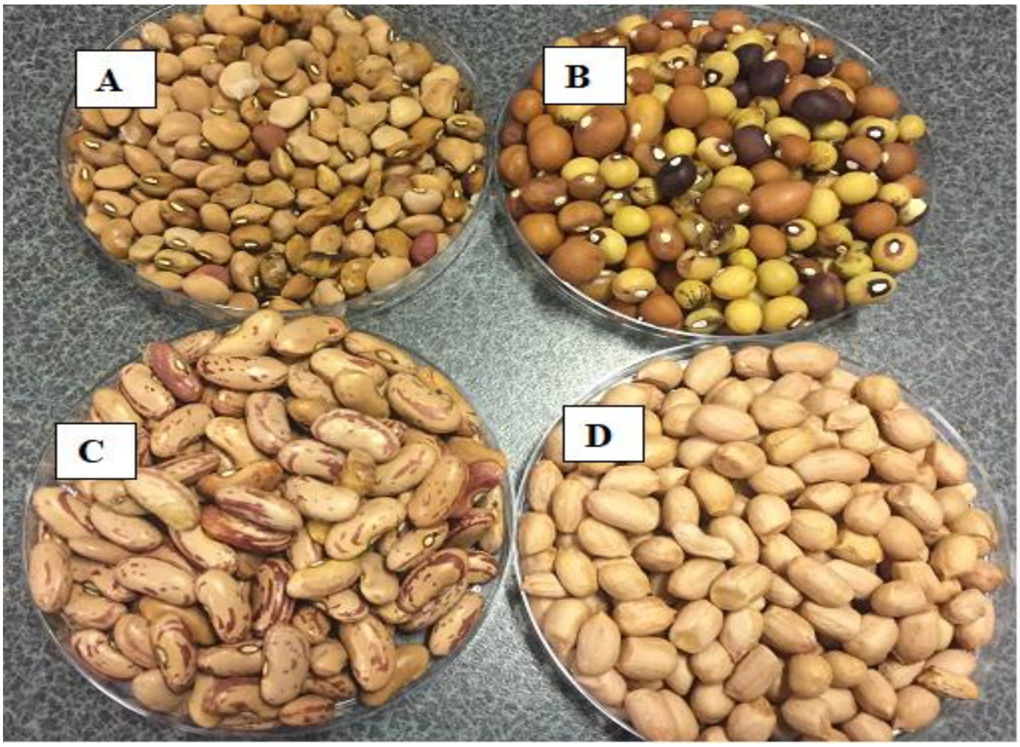

Figure 1. Seeds of selected varieties of indigenous grain legumes (A = cowpea—mixed brown; B = bambara groundnut—landrace) and major grain legumes (C = dry bean—Ukulinga; D = groundnuts—Kwarts).

2.3. Experimental Design and Trial Management

The experimental design at Ukulinga Research Farm, where there was access to irrigation, was a split-plot design arranged in randomised complete blocks with three replications. The main plots were water regimes (optimum irrigation, deficit irrigation and rainfed) while the subplots were the grain legume crops (dry bean, groundnut and bambara groundnut). Irrigation scheduling in the optimum irrigation was based on 80% management allowable depletion (MAD) total available water (TAW). The DI treatment was irrigated (MAD: 80% TAW) at the most sensitive to water stress growth stages (flowering and pod-filling stages). To determine the effect of environment, an experiment was conducted at the three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) under rainfed conditions. At all sites, the experimental design was a randomised complete block design with three replications. There was no cowpea at Ukulinga. At Umbumbulu, trials only established during the 2016/17 season.

At all the sites, plot size (sub-plot at Ukulinga) was 18.75 m2. Plant population was 26,667 plants hectare−1 for cowpea, 66,667 plants hectare−1 for bambara groundnut and 88,889 plants hectare-1 for dry bean and groundnut. During 2015/16, trials were planted on 17 November 2015 at Ukulinga and 4 December 2015 at Fountainhill. During 2016/17, trials were planted on

30 November, 14 December and 16 January 2016 at Umbumbulu, Fountainhill and Ukulinga, respectively. At planting, a slow release organic fertiliser [Gromor accelerator (0.3% N, 0.15% P and 0.15% K)] was applied at a rate of 4 000 kg ha−1 using the band placement method. Rate of fertilizer application was based on results of fertility analysis conducted prior to the experiment. Results showed that to meet the nutrient requirements of the grain legumes under study, there was need to add 120 and 50 kg ha^{-1} of N and P at Ukulinga and Fountainhill, while at Umbumbulu deficient N, P and K was 120, 50 and 10 kg ha^{-1}, respectively. For the duration of the trials, recommended best management practices (weeding, ridging and pest and disease control) for each crop were applied.

Table 1. Site characteristics of the three selected sites (Ukulinga Research Farm, Umbumbulu Rural District and Fountainhill Estate).

Site	**Ukulinga Research Farm**	**Umbumbulu Rural District**	**Fountainhill Estate**
Coordinates	29°37'S; 30°16'E	29°98'S; 30°70'E,	29°44'S; 30°54'E
Altitude (m.a.s.l.)	750	593	1020
Annual rainfall	694	1 200	905
Average temperature	25	28	20.4
Average max temperatures	26	27	29
Average min temperatures	10	13	17
Soil type	Heavy Clay	Clay-Loam	Sandy
Bio-resource group	Moist Coast Hinterland Ngongoni Veld	Moist Coast Forest, Thorn and Palm Veld (Moist Coast)	Moist Midland Mistbelt

2.4. Measurements

2.4.1. Yield and Yield Components

At harvest, six representative plants were randomly selected from each plot. Thereafter, the plants were air dried in a controlled environment situated at the UKZN Phytosanitary Unit until there was no change in total biomass. Pods were dehulled and grain mass was determined.

2.4.2. Determination of Evapotranspiration (ET)

Evapotranspiration for each treatment was calculated as the residual of a soil water balance (Allen et al., 1998);

$$ET = P + I - D - R - \Delta SWC \qquad \textbf{Equation 1}$$

where ET = evapotranspiration (mm), P = precipitation (mm), I = irrigation (mm), D = drainage (mm), R = runoff (mm), and ΔSWC = changes in soil water content (mm).

Daily rainfall (mm) was obtained from weather stations within a 10 km radius from the sites. At Fountainhill and Umbumbulu, daily rainfall data was obtained from the South African Sugar Association (SASA) weather web portal (http://portal.sasa.org.za/weatherweb). At Ukulinga, daily rainfall data was obtained from an automatic weather station (AWS), which is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW) network of automatic weather stations. Changes in soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta-T, UK). The sensors of the PR2/6 profile probe are positioned to measure volumetric water content at six depths (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe). The effective depth at Ukulinga was 0.40 m, hence the sensors positioned at 0.60 and 1.00 m were considered during analyses.

Drainage was considered as negligible. At Ukulinga, there was an impeding layer at 0.4 m which restricted downward movement of water beyond the root zone. At Fountainhill and Umbumbulu, drainage was considered negligible based on Dancette and Hall (Dancette and Hall, 1979) where in semi- and arid environments drainage is negligible if the profile is not periodically saturated to drain excess water. Runoff (R) was not quantified during the trials. However, to account for its effect the United States Department of Agriculture–Soil Conservation Service (USDA-SCS) procedure was used to estimate the monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to runoff (USDA-SCS, 1967). The soil water balance was therefore simplified to;

$$WU = ER + I - \Delta SWC$$ **Equation 2**

where:WU = water use = evapotranspiration (mm), ER = effective rainfall (mm), I = irrigation (mm), and ΔSWC = changes in soil water content (mm). Values of ET in mm (depth) were then converted to m3 (volume) using the formula;

$$\text{Volume } (m^3) = \text{Area } (m^2) \times \text{Depth } (m)$$ **Equation 3**

2.4.3. Determination of Nutritional Content (NC)

To preserve nutrients and avoid further metabolic reactions, grain was freeze-dried using a model RV3 vacuum freeze drier (Edwards, United States of America) after yield determination. Thereafter, samples were ground using a coffee grinder (Mellerware, South Africa) and sent to the KZN Department of Agriculture and Rural Development Plant Nutrition Lab. The nutrients analysed per dry matter basis included macro-nutrients (fat and protein) and micro-nutrients [calcium (Ca), zinc (Zn), iron (Fe)].

Determination of macro nutrients (fat and protein) followed the Association of Official Analytical Chemists (AOAC) standard procedures for nutrient analysis (Horwitz et al., 1970).

Dry matter was determined by drying samples in a fanned oven at 100°C for 24 hours. Nitrogen (N) was determined by the micro-Kjeldahl method. Thereafter, crude protein was calculated as;

$$N \times 6.25 \qquad \textbf{Equation 4}$$

Crude fat was determined according to the soxhlett procedure. Ash was determined by igniting fibre samples in a furnace at 550°C overnight. The carbohydrate content was then determined as the difference between 100% and addition of the percentages of moisture, fat, crude protein, and crude fibre. The mineral composition (Ca, Zn, Fe) were determined using the dry ashing (DA) technique (Horwitz et al., 1970). An aliquot of 25 ml was placed in crucibles. Thereafter, samples were placed in an oven set at 50°C to heat overnight. Following this, crucibles with residues obtained after vaporisation of water and most organic compounds were introduced in a high temperature muffle furnace and ashed at 450°C for 24 hours. Thereafter, samples were cooled and residues treated with nitric acid while on warm hot plate. Samples were then transferred back to the muffle furnace for 24 hours. White ashes obtained were dissolved in a beaker with 20ml 5% (v/v) nitric acid. The solution was then transferred to a 25 ml volumetric flask by rinsing with 5% v/v nitric acid. The solution then was used to determine Ca, Zn, Fe using an atomic absorption spectrophotometer (AAS) (Analytikjena AG, Germany).

2.4.4. Determination of Nutritional Water Productivity (NWP)

Nutritional water productivity was calculated based on the formula by Renault and Wallender (Renault and Wallender, 2000):

$$NWP = (Y/ET) \times NC \qquad \textbf{Equation 5}$$

where NWP is the nutritional water productivity (nutrition m^{-3} of water evapotranspired), Y is the harvested grain yield ($kg \cdot ha^{-1}$), ET is the actual evapotranspiration ($m^3 \cdot ha^{-1}$), and NC is the nutritional content per kg of product (nutrition unit$\cdot kg^{-1}$).

2.5. Data Analysis

Several factors affected the final data collection. In particular, data for cowpea were missing at Ukulinga due to animal attacks, hence no cowpea data are reported for both 2015/16 and 2016/17 season. At Umbumbulu, there was a hailstorm during 2015/16 which damaged plants. This occurred after the planting window and experiments could not be replanted, hence no data are reported for Umbumbulu during 2015/16. These considerations were taken into account as part of data analyses. Data from Ukulinga (the water treatments) and from the three sites (rainfed trials) were analysed separately. For both data sets, data of the two seasons (2015/16 and 2016/17) were subjected to Bartlett's test for homogeneity of variance in GenStat® 18th Edition (VSN International, UK). Results of both data sets showed evidence of non-homogeneity between the two seasons hence a separate analysis of the seasons was conducted. The data sets (the water treatments) and (the three sites) were subjected to analysis of variances (ANOVA) using GenStat® version 18 (VSN International, UK). Least significance difference (LSD) was used to separate means at the 5% level of significance.

3. Results

3.1. Rainfall

Total rainfall at Ukulinga and Fountainhill during 2015/16 was 445 and 583 mm, respectively. During 2016/17, total rainfall observed at Ukulinga, Fountainhill and Umbumbulu was 235, 395 and 595 mm, respectively. At Ukulinga during 2015/16, ≈ 25% of the total rainfall (120 mm) was received in two rainfall events [68 and 120 days after planting (DAP)] (Figure 2). During 2015/16, daily rainfall at Fountainhill did not exceed 45 mm and it was observed that ≈ 20% of the total rainfall was received during the first 14 days while ≈ 25% was received between 95 and 106 DAP. At Ukulinga, during 2016/17, rainfall did not exceed 30 mm for all the rain days. In addition to being low (235 mm), rainfall was also sparsely distributed (Figure 2). At Umbumbulu, where the highest rainfall was observed during 2016/17 (595 mm), it was observed that 120 mm of this rainfall was received in two days (72 and 97 DAP).

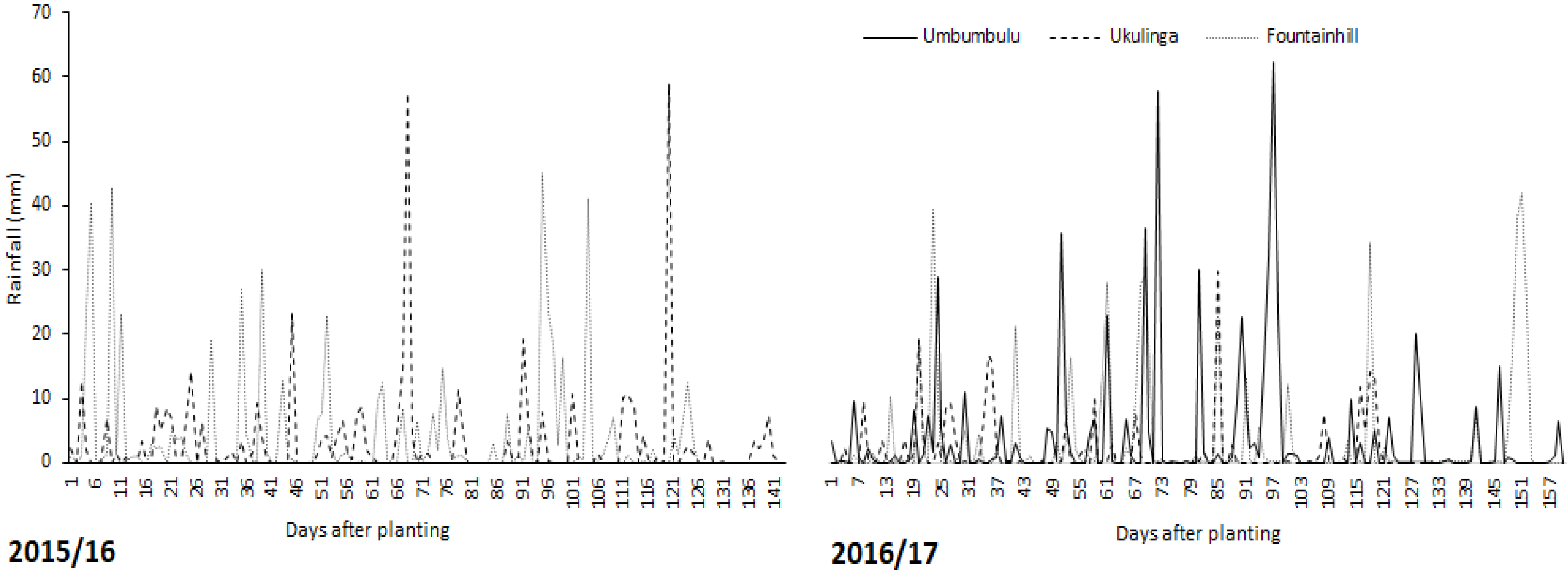

Figure 2. Rainfall (mm) observed at three sites (Ukulinga Research Farm, Umbumbulu Rural District and Fountainhill Estate) during 2015/16 and 2016/17 season

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3.2. Nutritional Content in Response to Water Regimes

With respect to fat content, it was observed that groundnut had the highest fat content across all seasons and water treatments (Table 2). For fat content, groundnut had > 900% more than the other crops, across all seasons and water treatments. During 2016/17, bambara groundnut fat content was as low as 6 $g{\cdot}kg^{-1}$. For all the crops, there was no discernible pattern with respect to the water treatment (Table 2). However, during 2015/16, groundnut fat content under the RF treatment was ≈ 100 $g{\cdot}kg^{-1}$ less than under OI and DI. Groundnut had more protein content during 2015/16, though the differences were not as high as for fat content. Bambara groundnut had the lowest protein content (200 – 258 $g{\cdot}kg^{-1}$) (Table 2). The highest difference between protein of groundnut and dry bean was 14%. This was observed under RF conditions. During 2016/17 dry bean had the highest protein under RF conditions (287 $g{\cdot}kg^{-1}$), and the lowest protein under DI (247 $g{\cdot}kg^{-1}$) (Table 2).

For the micronutrients, dry bean had the highest Ca content during 2015/16 under all the water treatments. Under rainfed conditions, Ca content in dry bean was ≈ 100% more than groundnut and bambara groundnut. During 2016/17, bambara groundnut showed high Ca content under DF conditions (100% more than dry bean) (Table 2). Contrary to the macronutrients, groundnut was inferior to dry bean and bambara groundnut, showing the lowest Ca content (100 $mg{\cdot}kg^{-1}$). For Zn and Fe content there was no clear pattern between the crops and the water treatments. For Zn content, the differences between the crops ranged between (5 – 15% which was lower compared to the differences observed for fat content (22 – 900%). For Fe content, it was observed that during 2015/16, dry bean had 200–350% more Fe content compared to bambara groundnut and groundnut under all the water treatments. Groundnut had the lowest Fe (Table 2). During 2016/17, it was interesting to observe that under OI, bambara groundnut had the highest Fe content (84.1 $mg{\cdot}kg^{-1}$), while groundnut had the highest Fe content under DI (102.9 $mg{\cdot}kg^{-1}$) and dry bean had the highest Fe under RF (104.6 $mg{\cdot}kg^{-1}$) (Table 2).

Table 2. Macro (protein and fat) and micro (Ca, Zn and Fe) nutrients of four grain legume crops (groundnut, bambara groundnut, dry bean and cowpea) grown under varying water regimes (optimum irrigation, deficit irrigation and rainfed) over two seasons (2015/16 and 2016/17).

			Fat	**Protein**	**Ca**	**Zn**	**Fe**
			$g\cdot kg^{-1}$		**$mg\cdot kg^{-1}$**		
2015/16	OI	Groundnut	406.65	290.16	710	44.43	38.00
		Bambara	10.24	210.55	670	28.27	39.01
		Dry Bean	50.27	260.18	1270	30.67	85.04
	DI	Groundnut	400.04	310.58	600	37.31	35.02
		Bambara	40.06	200.82	630	32.82	39.03
		Dry Bean	40.36	300.89	990	44.03	103.04
	RF	Groundnut	301.19	310.19	550	37.12	30.09
		Bambara	10.27	230.87	590	33.23	42.00
		Dry Bean	40.60	270.32	1400	33.95	87.00
2016/17	OI	Groundnut	405.44	249.77	860	32.92	47.90
		Bambara	57.24	231.13	580	30.36	84.17
		Dry Bean	10.13	287.77	1 170	33.28	69.60
	DI	Groundnut	418.50	288.82	1 110	32.79	102.96
		Bambara	6.21	258.88	1 260	32.59	60.75
		Dry Bean	62.99	247.72	650	25.07	70.01
	RF	Groundnut	438.79	275.59	100	35.70	63.84
		Bambara	59.57	205.55	600	29.47	42.47
		Dry Bean	17.90	270.03	1140	29.39	104.64

3.3. Nutritional Content in Response to Environments

Across environments, groundnut maintained its superiority with respect to fat content. Groundnut maintained a high fat content of > 900% compared to the other crops. The lowest fat content (4.87 g·kg^{-1}) was observed for cowpea at Fountainhill during 2016/17. Under the water treatments, there was no discernible pattern of crop performance with respect to protein content. Across environments however, groundnut had the highest protein content during both seasons 275 – 325 g·kg^{-1}). It was also observed that bambara groundnut had the lowest protein content across environments (205 – 253 g·kg^{-1}). During 2016/17, for all the crops, the lowest protein content was observed at Ukulinga (205 – 275 g·kg^{-1}) relative to Fountainhill (214 – 325 g·kg^{-1}) and Umbumbulu (225 – 316 g·kg^{-1}) (Table 3).

Under the water regimes, high Ca content in dry bean was limited to 2015/16 (Table 3). Under different environments, dry bean had the highest Ca content during both seasons (1.24 – 1.54 mg kg^{-1}) (Table 3). At Fountainhill and Umbumbulu, cowpea, had the 2nd highest Ca content (740 – 1370 mg·kg^{-1}) after dry bean. Groundnut, had the highest fat and protein but had the lowest Ca content at Ukulinga and Fountainhill during both seasons (< 550 mg·kg^{-1}). Similar to water treatments, there was no clear pattern on crop performance with respect to Zn content across environments (Table 3). However, it was observed that during both seasons, cowpea had the highest Zn content at Fountainhill (67.8 and 53.8 mg·kg^{-1}). It was also observed that at all sites during 2015/16 and at Umbumbulu and Fountainhill during 2016/17, bambara groundnut had the lowest Zn (< 33.2 mg·kg^{-1}). For bambara groundnut and cowpea, there was a Zn content difference of ≈ 100%, with cowpea having the highest (Table 3). For Fe content, dry bean and cowpea had the highest Fe content (61.6 – 104.6 mg·kg^{-1}). Fe in groundnut and bambara groundnut, ranged between 21.3 and 63.8 mg kg^{-1}, 100 – 300% lower than dry bean and cowpea (Table 3). Comparing the environments, it was observed that all the crops had the highest Fe (42.4 – 104.6 mg·kg^{-1}) at Ukulinga during 2016/17. This was the environment where all the lowest protein for all the crops was observed (Table 3).

Table 3. Macro (protein and fat) and micro (Ca, Zn and Fe) nutrients of four grain legume crops (groundnut, bambara groundnut, dry bean and cowpea) grown at three different sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) over two seasons (2015/16 and 2016/17).

			Fat	**Protein**	**Ca**	**Zn**	**Fe**
			$g \cdot kg^{-1}$		**$mg \cdot kg^{-1}$**		
2015/16	Ukulinga	Groundnut	300.19	310.19	550	37.23	30.93
		Bambara groundnut	10.27	230.87	590	33.31	42.09
		Dry Bean	40.60	270.32	1400	33.59	87.02
	Fountainhill	Groundnut	430.15	325.87	310	45.86	29.64
		Bambara groundnut	40.36	214.54	460	30.95	28.03
		Dry Bean	14.32	282.61	1240	42.52	85.04
		Cowpea	47.13	272.99	740	67.38	96.86
2016/17	Ukulinga	Groundnut	438.79	275.59	100	35.02	63.46
		Bambara groundnut	59.57	205.55	600	29.71	42.72
		Dry Bean	17.90	270.03	1140	29.94	10.42
	Fountainhill	Groundnut	470.29	324.42	330	46.49	21.75
		Bambara groundnut	47.42	253.20	620	28.86	23.98
		Dry Bean	14.26	277.82	1540	42.28	76.46
		Cowpea	4.87	314.06	1160	51.76	60.84
	Umbumbulu	Groundnut	448.75	316.12	510	41.61	26.91
		Bambara groundnut	61.74	225.55	380	27.05	21.24
		Dry Bean	22.91	303.86	1430	42.23	67.96
		Cowpea	12.09	295.92	1370	40.20	61.04

3.4. Nutritional Water Productivity in Response to Water Regimes

During 2015/16, results of yield and NWP for all the nutrients (protein, fat, Ca, Zn and Fe) showed significant differences ($P < 0.05$) among the crops. Water treatments were not significantly different ($P > 0.05$) (Table 4). The interaction between water treatments and crops was significantly different ($P < 0.05$) for grain yield, NWP_{fat} and $NWP_{protein}$. Under OI, the highest yield was observed for dry bean (2260 $kg \cdot ha^{-1}$). Dry bean also had the lowest ET (2680 m^{-3}) translating to high productivity (Table 4). This resulted in the highest $NWP_{protein}$ (220 $g \cdot m^{-3}$), despite the crop not having the highest protein content under OI. The high Ca (1270 $mg \cdot kg^{-1}$) and Fe content (85 $mg \cdot kg^{-1}$) observed for dry bean under OI translated to high NWP_{Ca} (1060 $mg \cdot m^{-3}$) and NWP_{Fe} (71.9 $mg \cdot m^{-3}$). Groundnut had high fat content resulting in the highest

NWP_{fat} (249 g·m^{-3}). For bambara groundnut, low NWP for all the nutrients was as a result of combined effect of low yield, high ET and low nutritional content (Table 4).

In addition to the high fat and protein content observed for groundnut under DI, it had the highest yield (200% more than the other crops) (Table 5). This resulted in higher $NWP_{fat\ and\ protein}$ (4956 kcal·m^{-3}, 406 g·m^{-3}, 314 g m^{-3}) under DI. It was interesting to observe that despite groundnut having the lowest Ca and Fe, it had the second highest $NWP_{Ca\ and\ Fe}$, (590 and 35.1 mg m^{-3}, respectively) because of the high grain yield (2900 kg·ha^{-1}) (Table 5). For bambara groundnut, results were consistent to the OI treatment — it had the lowest NWP for all the nutrients. Dry bean had the highest $NWP_{Ca\ and\ Fe}$ (> 300% more than groundnut and bambara groundnut) (Table 4).

During 2016/17, results of grain yield and NWP were similar to 2015/16 — significantly different among crops ($P < 0.05$) and not significantly different among water treatments ($P > 0.05$) (Table 5). The interaction between crops and water regime was only significant for $NWP_{fat,\ Ca\ and\ Fe}$. During 2016/17, dry bean had the highest grain yield (1 081 – 1 296 kg·ha^{-1}) and lowest ET (1 430 – 1 950 m^{-3}) across all water treatments. As a result, the highest $NWP_{protein,\ Ca,\ Zn\ and\ Fe}$ was highest for dry bean across water treatments. Although groundnut had 800% more fat under DI, dry bean had a higher NWP_{fat} (42 g·m^{-3}) due to the high grain yield and low ET. During 2015/16, groundnut performed better than bambara groundnut. In 2016/17 due to low grain yield for bambara groundnut and groundnut, the crops had similar $NWP_{protein,\ Ca,\ Zn\ and\ Fe}$ despite groundnut having higher nutrient content than bambara groundnut (Table 2 and 5).

Table 4. Yield, Evapotranspiration (ET) and nutritional water productivity (NWP) (protein, fat, Ca, Zn, and Fe), of three legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (OI, DI and RF) during the 2015/16 season.

Water Treatments	**Crop Species**	**Grain yield**	**ET**	**NWP$_{fat}$**	**NWP$_{protein}$**	**NWP$_{Ca}$**	**NWP$_{Zn}$**	**NWP$_{Fe}$**
		kg·ha^{-1}	**m^{-3}**	**——— g·m^{-3} ———–**		**————— mg·m^{-3} ————**		
OI	Dry bean	2260a	2680	44.00c	220.30b	1060a	25.80	71.90a
	Groundnut	1950ab	3160	249.20b	178.80c	440b	27.20	23.30b
	Bambara groundnut	1480b	3170	5.80c	100.70d	310c	13.20	18.30b
DI	Dry bean	1400b	2390	27.30	193.30b	620b	27.50	64.70a
	Groundnut	2900a	2920	406.00a	314.70a	590b	37.20	35.10b
	Bambara groundnut	1410b	2630	21.80c	111.60d	340c	17.60	21.10b
RF	Dry bean	1960a	2380	38.00c	225.40b	1150a	28.00	71.80a
	Groundnut	2770a	2830	308.20b	305.60a	450b	36.40	30.30b
	Bambara groundnut	1090b	2770	5.00c	94.40d	230c	13.10	16.70b
Significance (*p* = 0.05)	Crops	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001
	Water regime	* ns		* ns	* ns	* ns	* ns	* ns
	Crops * Water regime	0.031		0.028	0.040	* ns	* ns	* ns
	LSD $_{(p = 0.05)}$	1069		78.00	32.20	410		26.63

* ns: Not significant at $p = 0.05$.

Table 5. Yield, water use and NWP (protein, fat, Ca, Zn, and Fe), of three legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (OI, DI and RF) during the 2016/17 season.

Water Treatments	Crop Species	Grain Yield	ET	NWP_{fat}	$NWP_{protein}$	NWP_{Ca}	NWP_{Zn}	NWP_{Fe}
		kg·ha^{-1}	m^{-3}	g·m^{-3}		mg·m^{-3}		
OI	Dry bean	1296a	1950	6.70d	191.00a	1140a	22.90a	81.20a
	Groundnut	585b	3450	68.60a	42.30b	140b	5.57b	46.20b
	Bambara groundnut	466b	3060	8.70d	35.10b	80b	4.61b	12.80c
DI	Dry bean	1098a	1630	42.40b	166.30a	430b	16.86a	47.10b
	Groundnut	362b	2800	34.70c	23.90b	90b	2.72b	8.50c
	Bambara groundnut	402b	2560	1.10e	45.00b	220b	5.67b	10.60c
RF	Dry bean	1081a	1430	13.50d	204.00a	1110a	22.18a	79.00a
	Groundnut	267b	2490	46.90b	29.50b	100b	3.82b	6.80c
	Bambara groundnut	292b	2320	7.50d	25.90b	80b	3.71b	5.30c
Significance ($p = 0.05$)	Crops	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001
	Water regime	* ns		* ns	* ns	* ns	* ns	* ns
	Crops * Water regime	* ns		<0.001	* ns	0.022	* ns	<0.001
	LSD $_{(p = 0.05)}$	538.5		11.17	72.30	380	8.30	24.42

* ns: Not significant at $p = 0.05$.

3.5. Nutritional Water Productivity in Response to Environments

During 2015/16, sites were not significantly different for grain yield ($p > 0.05$) while NWP for all the nutrients (protein, fat, Ca, Zn and Fe) was significantly different ($p < 0.05$). Grain yield and NWP for all the nutrients (protein, fat, Ca, Zn and Fe) were significantly different ($P < 0.05$) among the crops (Table 6). The interaction between crop and site was significant ($P < 0.05$) for grain yield and NWP for all the nutrients (protein, fat, Ca, Zn and Fe). At Fountainhill, despite bambara groundnut having the highest yield (1 978 kg·ha^{-1}), it did not have the highest NWP for all the nutrients because of high ET (4 370 m^{3}) and low nutritional content (Table 3 and 6). Groundnut had the highest macro nutrient content (Table 2.3) which was translated to the highest $NWP_{\text{, fat and protein}}$ (2 575 kcal·m^{-3}, 197 g·m^{-3}, 148 g m^{-3}, respectively). Dry bean had the highest $NWP_{\text{Fe and Ca}}$ (> 39.7 mg·m^{-3} and > 570 mg m^{-3}). Despite low grain yield of cowpea, it had the highest NWP_{Zn} (26.3 mg m^{-3}) due to the high Zn content (67.8·mg kg^{-1}). Comparing the two sites, it was observed that Ukulinga yielded better (1 950 kg ha^{-1} and had lower ET (2 660 m^3) than Fountainhill (1 560 kg·ha^{-1} and 3 547 m^3, respectively. This led to 60 – 110% higher NWP for all the nutrients (protein, fat, Ca, Zn and Fe) at Ukulinga compared to Fountainhill.

During 2016/17, results of crops were significantly different ($P < 0.05$) for NWP$_{\text{fat, Ca, Zn and Fe}}$. For sites, NWP$_{\text{protein, Ca, Zn and Fe}}$ were significantly different ($P < 0.05$). The interaction between crop and site was significantly different ($P < 0.05$) for NWP$_{\text{fat, protein and Zn}}$ (Table 7). During 2015/16, it was observed that Ukulinga was better performing than Fountainhill. In 2016/17, Fountainhill was the best performing site. At Fountainhill, grain yield, NWP$_{\text{fat, protein, Ca and Zn}}$ was ≈ 100% more than at Umbumbulu and Ukulinga. Groundnut had the highest NWP$_{\text{fat and protein}}$ at Fountainhill and Umbumbulu (Table 7). At Ukulinga, dry bean grain yield was high, and ET was low, contributing to the highest NWP$_{\text{protein}}$ (2 347 kcal·m^{-3} and 204 g·m^{-3}, respectively). Similar to results of 2015/16, dry bean had the highest NWP$_{\text{Fe}}$ at Ukulinga and Fountainhill (79 and 46.6 mg·m^{-3}), however due to the low grain yield at Umbumbulu (282 kg·ha^{-1}), the crop did not have the highest NWP$_{\text{Fe}}$ (9.1 mg·m^{-3}).

Table 6. Yield, ET and NWP (protein, fat, Ca, Zn, and Fe), of four legume crops (dry bean, cowpea, groundnut and bambara groundnut) grown at two sites (Fountainhill Estate and Ukulinga Research Farm) during 2015/16 season.

Water Treatments	**Crop Species**	**Grain yield**	**ET**	**NWP_{fat}**	**$NWP_{protein}$**	**NWP_{Ca}**	**NWP_{Zn}**	**NWP_{Fe}**
		$kg \cdot ha^{-1}$	**m^{-3}**	**$g \cdot m^{-3}$**		**$mg \cdot m^{-3}$**		
Fountainhill	Dry bean	1456ab	3130	6.64c	131c	570b	19.87b	39.73b
	Groundnut	1594ab	3490	197.05b	148.8c	140c	21.00b	13.36c
	Bambara groundnut	1978a	4370	18.26c	97.1c	200c	13.89c	12.90c
	Cowpea	1214b	3200	18.28c	105.8c	280c	26.30b	37.33b
Ukulinga	Dry bean	1960a	2380	38.00c	225.40b	1150a	28.00a	71.80a
	Groundnut	2770a	2830	308.20a	305.60a	450b	36.40a	30.30b
	Bambara groundnut	1090b	2770	5.00c	94.40c	230c	13.10c	16.70c
Significance	Crops	0.032		<0.001	<0.001	<0.001	0.001	<0.001
	Site	* ns		0.003	<0.001	<0.001	0.007	<0.001
	Crops * Site	0.003		0.002	0.007	0.002	0.046	0.015
	LSD (P = 0.05)	745.9		44.38	63.27	180	8.76	12.48

* ns: Not significant at P = 0.05.

Table 7. Yield, water use and NWP (protein, fat, Ca, Zn, and Fe), of four legume crops (dry bean, groundnut and bambara groundnut) grown under three water treatments (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District) during 2016/17 season.

Site	Crop Species	Grain Yield	ET	NWP_{fat}	$\text{NWP}_{\text{protein}}$	NWP_{Ca}	NWP_{Zn}	NWP_{Fe}
		kg·ha^{-1}	m^{-3}	——— g·m^{-3} ———		———mg·m^{-3}———		
Fountainhill	Dry bean	1302a	2140	8.67c	169a	930a	25.80	46.67b
	Groundnut	2387a	2870	390.8a	269.6a	270b	38.61	18.09c
	Bambara groundnut	1359a	2650	24.31c	129.8	310b	14.86	12.25c
	Cowpea	1011a	2730	1.80c	116.3b	420b	19.16	22.32c
Umbumbulu	Dry bean	282c	2080	3.10d	41.2b	190b	5.96	9.12c
	Groundnut	1213a	2340	231.91b	163.4a	260b	21.43	13.96c
	Bambara groundnut	725b	2840	15.6c	57.6b	90b	7.1	5.44c
	Cowpea	953ab	3340	1.80c	84.4b	390b	11.56	17.58c
Ukulinga	Dry bean	1081a	1430	13.50c	204.00a	1110a	22.18	79.00a
	Groundnut	267b	2490	46.90c	29.50b	10c	3.82	6.80c
	Bambara groundnut	292b	2320	7.50c	25.90b	80b	3.71	5.30c
Significance	Crops	* ns		<0.001	* ns	0.008	0.027	0.006
	Site	0.002		* ns	0.010	0.012	0.002	0.010
	Crops * Site	* ns		<0.001	0.004	* ns	0.007	* ns
	LSD (P = 0.05)	1007.3		91.89	113.5	350		17.33

* ns: Not significant at *P* = 0.05.

4. Discussion

The objectives of the study were to determine the nutrient content and NWP of selected indigenous and major grain legumes in response to water regimes and production environments. To the best of our knowledge, this is the first study providing a comparative study of nutritional content and NWP of indigenous and major grain legumes grown under the same conditions. Previous studies that have compared nutritional content and NWP of grain legumes have relied on information obtained from a range of studies that were conducted under different environmental conditions (Renault and Wallender, 2000; Wenhold et al., 2012).

Crops differed in their nutritional content. Groundnut had higher fat content relative to the other crops; a 100 g serving of groundnut can supply the Recommended Dietary Allowance (RDA) of fat (40–78 g). A gram of fat contains ≈ 37.6 kJ of energy, hence fat rich foods are good sources of energy. The high fat content of groundnut has been explored through processing into peanut butter and extraction of oil for household use. This makes groundnut a multi-purpose grain legume, and partly explains the reason why groundnut is an important and major grain legume. However, over consumption of groundnut poses risk associated with excess fat consumption, which is one of the major causes of obesity (Ros, 2010; United Nations Development Programme (UNDP), 2012). In semi- and arid regions, 30% of the population is overweight and obese (IFPRI, 2016), hence the promotion of groundnut needs to be accompanied with proper consumption recommendations. This also supports the need to diversify grain legumes to avoid over reliance on a few major legumes such as soybean and groundnut that have high fat content.

For all the grain legumes, protein content was between 205 and 325 $g \cdot kg^{-1}$, implying that a 100 g portion of legume supplies 40–60% of protein RDA (50 g). This confirms arguments that legumes can be promoted as alternatives to meat, to avoid protein energy malnutrition (Chibarabada et al., 2017; Foyer et al., 2016). Legumes have also been associated with containing appreciable amounts of micronutrients (Akinyele and Shokunbi, 2015; Boschin and Arnoldi, 2011; Seena and Sridhar, 2005). In the semi- and arid regions, Fe, Ca and Zn are among the problematic micronutrients as their deficiency has devastating consequences such as anaemia in women of reproductive age and birth defects in children (UNDP, 2012). For Fe, Ca, Zn, the RDA for an adult is 18 mg, 1000 mg and 11 mg, respectively. Fruits and vegetables are the major sources of micronutrients, but they are not always available due to price and seasonality. Dry bean and cowpea have the potential to supply 40 to 60% of Fe and Zn RDA. In the case of Zn, this study showed that cowpea and dry bean contained ≈ 500% more Zn than leafy vegetables that have been observed to contain 2.9 to 15.1 $mg \cdot kg^{-1}$ (Nyathi et al., 2016). While vegetables such as spider flower contain more Fe than grain legumes (200 $mg \cdot kg^{-1}$), Fe content of grain legumes is comparable to those observed for vegetables such as Swiss chard and cabbage (38.80–98.40 $mg\ kg^{-1}$) (Nyathi et al., 2016.). This study brings a new perspective that vegetables are not the only major source of micronutrients but legumes' micronutrient value is comparable to that of leafy vegetables. This supports the role of legumes in increasing dietary diversity as they can complement cereals and vegetables in diets to meet the required nutrients for a healthy life (Chibarabada et al., 2017).

Among the grain legumes under study, bambara groundnut had the lowest macro- and micro nutrient content. Nutrient content of bambara groundnut observed in this study were in the same range of those observed in other studies (Amarteifio et al., 2006; Brough and Azam-Ali, 1992; Kudre and Benjakul, 2013). Amarteifio et al. (2006) assessed micronutrient content of various landraces from Botswana, Namibia and Swaziland. They observed large variability within landraces and interestingly landraces from Swaziland had higher micronutrient content than landraces from Namibia and Botswana. This demonstrates that some bambara groundnut landraces are more nutrient dense than others. Findings of this study are a first, as they suggest that non - uniformity in nutrient content of bambara groundnut is not limited to different landraces but may also occur within the same landrace. This supports Massawe et al, (2003; 2005) who reported that a bambara groundnut seedlot maybe heterogenous and there can be a mixture of genotypes with highly diverse populations within a landrace. During 2016/17, bambara groundnut had ≈ 100% more Ca under DI compared to the other treatments. This non-uniformity in nutrient content within and across bambara groundnut landraces may hamper its promotion in the semi- and arid tropics. This calls for breeding efforts to select for nutrient dense landraces that can be used in breeding for high and uniform nutrient content.

Nutrient content of crops differed across water treatments and environments. When rainfall was low (Ukulinga during 2016/17), protein content for all the crops was also low. The low protein content under water limited conditions is attributed to low nitrogen (N) uptake by the plant. Nitrogen is correlated to protein content because it is important for synthesis of amino acids which are building blocks of proteins. Under water limited conditions, the activity of the enzyme that converts nitrogen to a form that is readily available to plants (nitrate reductase) is reduced (da Silva et al., 2011). This ultimately reduced N availability to the plant (da Silva et al., 2011), and consequently protein synthesis was reduced. This implies that water stress does not only affect yield, but can also affect protein content of crops. Fe content was higher at Ukulinga compared to the other sites. Fe is not readily mobile to different plant organs and its delivery to seeds depends on a continuous Fe transport system (Briat, 2005; da Silva et al., 2011). The moisture of soil affects Fe availability. Wet soils have greater Fe availability for plants due to higher Fe^{2+}/Fe^{3+} ratio (Briat, 2005; da Silva et al., 2011). Ukulinga was characterised by shallow soil profile and clay soil hence good water holding capacity. This could have enhanced Fe mobility from roots to seeds. Inherent environmental conditions influenced grain nutrient content but there is still a dearth of information on how inherent environmental conditions and plant nutrient availability affects grain nutrient content in different crops.

To the best of our knowledge, this is the first study to determine the NWP of grain legumes based on in situ measurements and not estimates, hence results are more reliable. Nutritional water productivity varied significantly among the crops. With respect to fat productivity, groundnut was the most productive producing up to 400 $g \cdot m^{-3}$, respectively. This was because of high fat content. For $NWP_{Fe,\ Zn\ and\ Ca,}$ dry bean was the most productive followed by cowpea. For groundnut, despite the high grain yield, $NWP_{Fe,\ Zn\ and\ Ca}$ was low due to poor nutrient content. This highlights the need for crop diversification to maximise nutritional productivity as crops showed different qualities. Fe, Zn and Ca contents of dry bean and cowpea observed in this study were comparable to those observed for leafy vegetables. However, $NWP_{Fe,\ Zn\ and\ Ca}$ observed for leafy vegetables by Nyathi et al. (2016) were higher (≈ 200%) than those observed by this study for grain legumes. This could be because leafy vegetables relatively used less water (1210–3260 m^{-3}) and had higher yield (600–9500 $kg \cdot ha^{-1}$) than the grain legumes under study. For maximum benefit of Fe, Zn and Ca under water limited conditions, vegetables would be the recommended option as they are more productive. This highlights the importance of merging aspects of water use, yield and nutritional content for effective recommendations on tackling food and nutritional security.

The major legumes (groundnut and dry bean), had the highest protein water productivity, relative to the indigenous grain legumes. In the case of groundnut, it was mostly as a result of high protein content and high yield observed for the crop. For dry bean, high protein water productivity was as a result of low ET and high protein content. For the indigenous grain legumes (cowpea and bambara groundnut), protein water productivity was low due to low protein content, high ET and low grain yield for bambara groundnut and low yield for cowpea. If indigenous grain legumes are to be promoted for crop diversification, there is need for yield and nutritional content improvements, to improve protein water productivity. When comparing protein water productivity values of grain legumes (100–300 $g \cdot m^{-3}$) to that estimated for meat products (12–60 $g \cdot m^{-3}$) (Wenhold et al., 2012), it is interesting to note that despite meat being the highest protein source, legumes are more productive. This is because water consumption in legume production is less than water consumption for production of meat. This further supports the promotion of legumes as protein alternatives in water scarce areas as they relatively use less water compared to production of meat (Wenhold et al., 2012).

Environments had a significant effect on NWP. This was mostly as a result of yield instability across environments. Fluctuations in NWP followed fluctuations in grain yield. Low grain yield caused low NWP. There has been emphasis on improving yield stability in the context of food security. This study highlights a new insight that yield stability also affects NWP and improving yield stability not only ensures continuous availability of grain but also ensures continuous nutritional gain. Water regimes did not have a significant effect on NWP. Grain yield was also not significantly affected by water regimes. This implies that there is scope to tackle the challenge of food and nutritional security in the semi- and arid tropics under rainfed conditions.

5. Conclusions

Groundnut had a higher fat content relative to the other crops. Dry bean and cowpea had the highest micronutrient and have potential to supply 40 to 60% of Fe and Zn RDA. This highlighted their potential in increasing dietary diversity as they can serve as complements to cereals and vegetables in diets to meet the required nutrients for a healthy life. The protein content of all the grain legumes showed potential to supply 40–60% of protein RDA. This confirmed the role of legumes as a source of dietary protein among poor rural people who may not be able to afford meat and dairy products. Bambara groundnut had the lowest macro- and micro nutrient content. In addition to the non-uniformity in nutrient content of different bambara groundnut landraces, this study was a first to observe non-uniformity in nutrient content within the same landrace. This calls for breeding efforts to breed for nutrient density and uniformity in bambara groundnut. Protein content reduced when rainfall was low. Fe content was higher under clay soil. This highlights that climate and edaphic conditions do not only affect yield but nutritional content also. The major legumes (groundnut and dry bean), had the highest protein water productivity, relative to the indigenous grain legumes. For NWP $_{\text{Fe, Zn and Ca,}}$ dry bean and cowpea were more productive. Environments had a significant effect on NWP, hence the hypothesis was rejected. Differences in NWP across environments were due to yield instability across environments. Yield stability of grain legumes is key to tackling food and nutrition insecurity. In the case of water regimes, the hypothesis could not be rejected as water regimes did not significantly affect NWP. This implies that there is scope to tackle the challenge of food and nutrition security in the semi- and arid tropics under rainfed conditions. While the results of the current study may be preliminary, they provide useful initial insights on how increasing food production and crop diversity can be linked to addressing nutritional outcomes. This study only provides a first insight about the nutrient content and nutritional water productivity of a limited number of selected grain legumes in response to the production environment. This first study therefore requires detailed follow-up studies to also include cowpea data. In addition, such future studies should provide more experimental data and explore effects of additional factors such as management practices (fertiliser levels and plant density), climate and edaphic factors on nutrient content and NWP for a range of legumes.

There is also need to explore the effect of antinutritional factors on nutritional value of grain legumes grown under different environments.

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CHAPTER 6

CALIBRATION AND TESTING OF AQUACROP FOR GROUNDNUT (*ARACHIS HYPOGAEA*) AND DRY BEAN (*PHASEOLUS VULGARIS*)

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Abstract

Groundnut (*Arachis hypogaea*) and dry bean (*Phaseolus vulgaris*) are important grain legumes in the semi– and arid tropics. AquaCrop model (V5.0) was calibrated and tested for its ability to simulate canopy cover (CC), biomass, yield and evapotranspiration (ET) of groundnut and dry bean under semi– and arid environments. The model was calibrated using data collected from field and controlled environments for 2015/16 summer season. The model was tested using data collected at three sites (Ukulinga, Fountainhill and Umbumbulu) during 2016/17 Model calibration showed that AquaCrop simulated CC and cumulative biomass well for both crops. The model overestimated ET for both crops by 21 – 38%. During model testing, the performed poorly for CC, cumulative biomass and final yield for groundnut at Ukulinga due to several attacks by monkeys. However, the model accurately estimated ET (-1 – 11%). For Fountainhill and Umbumbulu, the model performed well in simulating CC and cumulative biomass for groundnut. For dry bean testing, the model performed well under deficit irrigation and rainfed conditions. For optimum irrigation, CC was poorly simulated. For Fountainhill overall model performance was good. For Umbumbulu, overall model performance was poor for canopy cover and good for biomass accumulation. Evapotranspiration was overestimated by 27%. Overall the model showed potential for simulating yield and ET of groundnut and dry bean under semi-arid conditions. There is a need to further test the model under different soils and climates.

Keywords: grain legumes, semi-and arid environments, water regimes

1. Introduction

An increase in production of grain legumes is expected in semi– and arid regions following the promotion of sustainable intensification and alleviation of food and nutrition security. Currently, grain legumes have shown suitability to these environments, but they have also shown instability across environments and seasons. In these regions water remains one of the limiting factors to agriculture. There are gaps on how grain legumes adapt to different environments and to varying water availability. For successful promotion of legumes in semi– and arid regions there is need for information on their adaptability to these regions. This requires investments in time and resources on research, which are often limiting. Crop growth models have been developed partly to answer research questions, thus, limiting time and resources spent on carrying out field experiments under various environments and management (Dourago-Neto et al., 1998; Rauff and Bello, 2015).

Crop growth models mimic growth and development of crops under different conditions using empirical and mathematical relationships (Dourago-Neto et al., 1998; Rauff and Bello, 2015). They are useful decision support tools (Boote et al., 1996), making them valuable tools in agriculture. Grain legumes have been modelled successfully with groundnuts, soybeans and dry beans having their own models [PNUTGRO (Boote *et al*., 1989), SOYGRO (Jones et al., 1989) and BEANGRO (Hoogenboom et al., 1994), respectively], which are housed in the Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al., 2003). Legumes such as groundnut, soybean, cowpea and dry bean have also been calibrated for major models such as the Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003). While these models were successful in simulating yield under different management conditions (Bhatia et al., 2008; Yadav et al., 2012), their wider use has been limited by their complexity as they require a relatively large number of input parameters, of which some are challenging to obtain under field conditions (Corbeels et al., 2006; Mourice et al., 2014; Jones et al., 2017). This confines their application to research applications where resources, instrumentation and expertise are available. The FAO overcame the issue of complexity, by developing a simpler model that can still maintain accuracy and robustness – AquaCrop (Raes et al., 2009; Steduto et al., 2009).

The FAO - AquaCrop model was designed to model yield responses to water making it an appropriate model in semi– and arid regions (Raes et al., 2009; Steduto et al., 2009). AquaCrop has been successfully parameterized for several herbaceous crops including, but not limited to, wheat (*Triticum aestivum*) (Andarzian et al., 2011), maize (*Zea mays*) (Heng et al., 2009) sorghum (*sorghum bicolor*) (Araya et al., 2016) and cotton (*Gossypium spp.*) (Farahani et al., 2009). Thus far, a few grain legume crops such as soybean (*Glycine max*) (Steduto et al., 2012; Adeboye et al., 2017), bambara groundnut (*Vigna subterranea*) (Karunaratne et al., 2011; Mabhaudhi et al., 2014a) and pea (*Pisum sativum*) (Paredes and Torres, 2016) have been calibrated and tested for AquaCrop. For these crops, AquaCrop was able to predict yield under different production scenarios (Karunaratne et al., 2011; Mabhaudhi et al., 2014a, Paredes and Torres, 2016; Adeboye et al., 2017). For pea, AquaCrop was successfully applied to assess the impact of sowing dates and irrigation strategies on yield and water use (Paredes and Torres, 2016). AquaCrop could be a useful decision support tool on production of grain legumes in semi– and arid regions. This is currently limited as only a few grain legumes (soybean, bambara groundnut, pea) have been modelled in AquaCrop.

There is need to calibrate and test AquaCrop for more grain legume crops. Groundnut (*Arachis hypogaea*) and dry bean (*Phaseolus vulgaris*) are among the major grain legumes produced by subsistence and commercial farmers in the semi– and arid regions (Chibarabada et al., 2017). Currently, AquaCrop has not been calibrated and validated for both crops. Availability of well–calibrated models, is an initial step to increased application of AquaCrop to answer research questions on adaptability of grain legumes to varying water availability and environmental conditions. The aim of the study was to calibrate and test the performance of AquaCrop model for groundnut and dry bean under varying water regimes and environments in a semi– and arid environment. The specific objectives were to (i) calibrate AquaCrop for groundnut and dry bean, (ii) evaluate its ability to simulate CC, biomass, yield and evapotranspiration (ET) of groundnut and dry bean for varying soils and climates.

2. Material and Methods

2.1 AquaCrop Model

The FAO’s AquaCrop model is an engineering type, water–driven and canopy level model (Raes et al., 2009; Steduto et al., 2009) that builds on previous FAO work related to yield response to water (Doorenbos and Kassam, 1979). It simulates yield response to water availability. Yield is simulated using four phases which are; crop development, crop transpiration, biomass production and yield formation (Steduto et al., 2009; Vanuytrecht et al., 2014). AquaCrop is a canopy level model because it simulates crop development through the canopy’s expansion, aging, conductance and senescence. When simulating crop development, AquaCrop describes the green canopy which is above ground as well as development of root zone (below ground). To describe stresses on canopy expansion, AquaCrop uses stress coefficients (Ks) where; Ks is 1 when water stress is non-existent (above upper threshold) and Ks is 0 when water stress completely stops canopy expansion (below lower threshold) (Steduto et al., 2009; Vanuytrecht et al., 2014). In AquaCrop, CC is proportional to transpiration.

The same pathway for transpiration is used for CO_2 intake by the plant, which is then converted to carbohydrates through photosynthesis — hence transpiration is proportional to biomass production (Steduto et al., 2009; Vanuytrecht et al., 2014). The relationship between biomass produced and water consumed by a given species is linear for a given climatic condition, hence AquaCrop uses a normalized crop water productivity function [aboveground dry matter produced per unit land area or per unit of water transpired (mm)] in the simulation of biomass. This relationship is the core of AquaCrop and is where the description 'water driven' emanates from. The equation for the simulation of biomass is therefore (Steduto et al., 2009; Vanuytrecht et al., 2014);

$$B = WP \times \sum T_r, \qquad \textbf{Equation 1}$$

where,

B = Above ground biomass (tonne ha^{-1})

WP = Normalised water productivity (g m^{-2}), and

T_r = Crop transpiration (mm).

To calculate the yield, AquaCrop uses the harvest index (HI), taking into consideration the adjustments in HI due to stress at the start of the yield formation, during flowering and during yield formation (Steduto et al., 2009; Vanuytrecht et al., 2014). Therefore;

$$Y = f_{HI} \times HIo \times B, \qquad \textbf{Equation 2}$$

where:

Y = yield (tonne ha^{-1})

f_{HI} = multiplier which considers the stresses that adjust the HI from its reference value

HIo = Reference HI (%)

B = Total above ground biomass (tonne ha^{-1}).

To run simulations, AquaCrop requires inputs of climate data, crop characteristics, soil characteristics and description of management practices.

2.2 Study areas

Field trials were conducted at three sites (Fountainhill Estate, Ukulinga Research Farm and Umbumbulu Rural District), in KwaZulu-Natal, South Africa. Ukulinga Research Farm [29°37’S; 30°16’E; 750 meters above sea level (m.a.s.l.)] was the on-station research trial, while Umbumbulu (29.984’S; 30.702’E; 593 m.a.s.l.) and Fountainhill Estate (29.447’S; 30.546’E; 1020 m.a.s.l.) were on-farm research trials. A pot trial was conducted in a growth tunnel at the University of KwaZulu-Natal’s Controlled Environment Facility, Pietermaritzburg, South Africa (29°37'12"S; 30°23'49"E; 750 m.a.s.l.). The environment in the growth tunnel is semi-controlled with temperatures ranging from ~18/33°C (day/night) and relative humidity (60 – 80%), which is a warm subtropical climate (Modi, 2007).

2.3 Experimental design

2.3.1 Field Trials

Experiments were conducted during the 2015/16 and 2016/17 summer seasons. At Ukulinga Research Farm, the experimental design was a split-plot design arranged in randomised complete blocks. The main plots were the water treatments while subplots were the crops (groundnut and dry bean). The water treatments were optimum irrigation, deficit irrigation and rainfed conditions. Irrigation scheduling was based on management allowable depletion (MAD) of 60% Plant Available Water (PAW). The approach to deficit irrigation was to apply irrigation (MAD: 60% PAW) at the growth stages that were most sensitive to water stress (Geerts and Raes, 2009). All the water treatments were optimally irrigated up to 90% emergence to ensure establishment of all trials. For the rainfed trial, irrigation was withdrawn thereafter. At Umbumbulu and Fountainhill, the trials were entirely rainfed and the experimental design was a randomised complete block design with three replications. Plant population for both crops was 88 889 plants ha^{-1}. Trials from Ukulinga during the 2015/16 were used to calibrate the model while trials at all the sites during 2016/17 were used for model evaluation (Table 1). Planting dates for all the trials are given in Table 1.

2.3.2 Controlled environment

A pot trial was conducted during 2015/16 summer season for the purposes of determining some parameters needed to calibrate the model (Table 1). Planting date is given in Table 1. The experimental design included three water treatments (80, 60 and 30% of field capacity) and two grain legume crops (groundnut and dry bean), arranged in a completely randomised design with three replications (3×2×3 = 18 pots). The three water treatments [80, 60 and 30% of field capacity (FC)] represented no water stress, mild water stress and severe water stress, respectively. This was based on previous studies that used the same treatments to impose water stress in pot trials. In addition to the 18 pots, nine pots (three replications × three water treatments) were added to monitor soil evaporation from the pots. Soil evaporation was deducted from the total evapotranspiration of the pots to determine crop transpiration. Fifty-four pots representing (two legume crops × three water treatments × nine intervals) were also added to allow for destructive sampling to determine plant mass fortnightly. This allowed for correction of plant mass when determining irrigation through gravimetric measurements. In total, there were 81 pots.

Table 1: Summary of experimental design, planting dates and data sets used for calibration and testing of the model.

Season	Site	Water treatment	Planting date	Calibration	Testing
2015/16	Ukulinga	[a]OI	17 November 2015	✓	
		[b]DI		✓	
		Rainfed		✓	
2015/16	Pot trial	80% [c]FC	20 December 2015	✓	
		60% [c]FC		✓	
		30% [c]FC		✓	
2016/17	Ukulinga	[a]OI	16 January 2016		✓
		[b]DI			✓
		Rainfed			✓
	Fountainhill	Rainfed	14 December 2016		✓
	Umbumbulu	Rainfed	30 November 2016		✓

[a]OI = Optimum irrigation; [b]DI = Deficit irrigation; [c]FC = Field capacity

2.4 Model Inputs

2.4.1 Climate Data

To create a climate file (.CLI), the AquaCrop model requires daily maximum (Tmax) and minimum (Tmin) air temperatures (.TMP file), FAO Penman-Monteith daily reference crop evapotranspiration (.ETO), daily rainfall (.PLU) and mean annual carbon dioxide (CO_2) concentration. For Ukulinga, .TMP, .PLU and .ETO files were created using daily data obtained from an automatic weather station that is located at the Research Farm. For Fountainhill and Umbumbulu, .TMP, .PLU and .ETO were created using daily data obtained from the South African Sugar Association (SASA) weather web portal (http://portal.sasa.org.za/weatherweb). For all sites, a default file of the mean annual CO_2 concentration measured at the Mauna Loa Observatory in Hawaii that is provided by AquaCrop was used.

2.4.2 Crop parameters

The initial values for the conservative parameters were selected from relatively similar grain legume crops that have been calibrated for AquaCrop. For groundnut, a bambara groundnut crop file (Mabhaudhi et al., 2014a) was used. For dry bean the soybean.CRO [Default soybean, Calendar (Patancheru, 25Jun96)] in AquaCrop was used. The model was calibrated using data collected from the optimum irrigation treatment at Ukulinga during the 2015/16 season and the pot trials (Table 1). For parameters not measured during the experiments, values from the template crop files (bambara groundnut in the case of groundnut and soybean in the case of dry bean) parameters were used as they are relatively similar grain legumes.

Groundnut and dry bean crop files (.CRO) were created using data collected from Ukulinga during 2015/16 and pot trials. Crop parameters from the OI treatment were used to calibrate the model as they represent the crops' potential under no stress (Table 2). Data from the DI and rainfed irrigation treatments was used to determine crop response to water stress. In cases where data from field trials was inconclusive, data from pot trials were used to determine crop responses to water stress. Transpiration could not be determined under field conditions; hence WP was determined from the pot trial (Table 2). Parameters not considered were biomass production affected by soil salinity and fertility stress. Crop phenology was observed in calendar days and thereafter converted to thermal time (GDD) in AquaCrop. AquaCrop allows users to input phenology data in calendar days and by switching the model to the GDD mode, the parameters are automatically converted to GDD units based on the crop's base and upper temperature (Steduto et al., 2012).

Table 2: Selected crop parameters and values used for the calibration of groundnut and dry bean in AquaCrop.

Parameter	**Determination**	**Unit**	**Groundnut value**	**Dry Bean value**
Planting method		-	Direct sowing	Direct sowing
Plant population	Plant population based on intra-row spacing of 0.75 m and inter-row spacing of 0.15 m	Plants hectare^{-1}	88 889	88 889
Seedling size	Obtained under controlled environment where the mean initial seedling leaf area per plant was measured at 90% emergence on five randomly selected plants using the LI-3100C Leaf Area Meter (LICOR, USA).	cm^2	3	17
Initial canopy cover (CCo)	Model derived	%	0.27	1.51
Time to emergence	Time to emergence was determined as the number of days from planting to when 90% of the plants had > 20 mm hypocotyle protrusion.	Growing Degree days	127	89
Time to maximum canopy cover (CCx)	Leaf area index, which is the one–sided green leaf area per unit ground surface area occupied by the plant was measured with the LAI-2200C Plant Canopy Analyzer (LICOR, USA). LAI values were converted to CC using the formula by Hsiao et al. (2012) where; $CC = 1.005 \times [1 - \exp(-0.6\ LAI)]$ Graphs of weekly CC were plotted and the time to which the canopy reached its constant peak was determined as the maximum canopy cover.	Growing Degree days	1 040	949

Time to canopy senescence	Time taken when at least 10% of leaves had senesced (chlorophyll degradation) without new leaves being formed to replace them.	Growing Degree days	110	1 133
Time to physiological maturity	A plant matured when at least 50% of leaves had senesced (chlorophyll degradation).	Growing Degree days	132	1 559
CCx	Consistent maximum canopy observed.	%	68	70
Canopy decline	Time from maximum CC to when 50% of plants had reached senescence	days	23	20
Canopy growth coefficient (CGC)	Model derived	%/day	12.2	11.0
Canopy decline coefficient (CDC)	Model derived	%/GDD	0.683	0.745
Length building up HI	Time from flowering (50% of the plants had at least one open flower) to maturity (50% of plants reached physiological maturity).	Growing Degree days	943	846
Duration of flowering	This was defined as the period (number of days) that 50% of the experimental plants had at least one flower that was open.	Growing Degree days	798	641
Time to flowering	This was the time taken for 50% of the experimental plants to have at least one fully opened flower.	Growing Degree days	595	640
Determinacy linked with flowering	Determinancy was defined as cessation of vegetative growth when the terminal flower of the main stem started to develop.	–	No	Yes
Minimum effective rooting depth	Plants used for determination of seedling CC were used for determination of minimum effective rooting depth. Seedlings were sampled at 90% emergence and root length was measured using a 30-cm ruler.	m	0.3	0.3

Upper temperature	Upper temperatures were obtained from Vara Prasad et al. (2002) and Vara Prasad et al. (2001), respectively.	°C	28	29
Maximum air temperature affecting pollination	Obtained from Vara Prasad et al. (2002) and Vara Prasad et al. (2001), respectively.	°C	34	34
Water productivity (WP)	This was obtained from the pot trials under 80% FC. A duplicate trial (one with the plant and without the plant) was established. Evapotranspiration (ET) was measured in the pots with the plants while evaporation was measured in the pots without the plants. At the end E was deducted from ET to determine T. WP was then computed from the measured T and total plant biomass WP = Biomass (g)/ T (mm)	tonne ha^{-1}	15	12
Reference HI (HI_o)	Determined from the optimum irrigation trial as; HI = Yg/B where: Yg = economic yield based on grain yield (kg), and B = total biomass (groundnut)/ above ground biomass (dry bean) (kg).	%	24	43
Canopy expansion: (response to water stress)	Determined from values of weekly leaf area measured from the pot trial using the LI-3100C Leaf Area Meter (LICOR, USA).at different water regimes. Data on leaf area was analyzed to determine the crop thresholds and sensitivity class.	–	Moderately tolerant	Moderately tolerant

Stomatal closure (response to water stress)	Weekly stomatal conductance from three water regimes during the pot trial was measured using a Steady State Leaf Porometer Model SC-1 (Decagon Devices, USA) on the abaxial surface of a new fully expanded and fully exposed leaf. Data was analysed to determine sensitivity class.	–	Moderately sensitive	Moderately sensitive
Early canopy senescence (response to water stress)	Determined from values of time to senescence measured during the pot trial at different water regimes. Time taken when at least 10% of leaves had senesced (chlorophyll degradation) without new leaves being formed to replace them. Data on time to senescence was analyzed to determine the crop thresholds and sensitivity class.	–	Moderately tolerant	Moderately tolerant
Aeration stress to waterlogging	Obtained from Liu (2009) and Soltani (2015), respectively	–	Moderately tolerant	Moderately tolerant
Overview of water stress effects on HI	The positive difference between the HI_o and HI under rainfed conditions was considered as the overall positive impact of water stress on HI.	%	6	10

2.4.3 Soil parameters

Soil files (.SOL) for each site (Ukulinga, Umbumbulu and Fountainhill) were created using site specific soil data (Table 3). Soil characteristics at Ukulinga were obtained from Mabhaudhi et al. (2014b) who used the same field. At Fountainhill and Umbumbulu, soil physical characteristics (depth and texture) were determined and hydraulic properties were calculated using Soil Texture Triangle Hydraulic Properties Calculator (http://hydrology1.nmsu.edu/teaching/soil456/soilwater.html). There was no groundwater file (.GWT) created.

2.4.4 Irrigation and field management

Irrigation was applied through a sprinkler system with a distribution uniformity of 85% and 100% soil surface wetting. Three separate irrigation files (.IRR) for the fully irrigated, deficit and rainfed trial were created. For the field management file (.MAN), soil fertility was non-limiting, there was no mulching and soil bunds and there were no practices to prevent surface runoff.

Table 3: Soil parameters used for the AquaCrop Soil File

Site	**Horizon**	**Description**	**Thickness** (m)	**[a]Sat**	**[b]FC** ——(% Vol)——	**[c]PWP**	**[d]Ksat** (mm day^{-1})	**[e]TAW** (mm)
Ukulinga	1	Clay loam	0.40	48	40	21	25	78.4
Fountainhill	1	Sand	2.0	36	13	6	3000	140
	1	Clay loam	0.40	46	35	17	125	72
Umbumbulu	2	Clay	0.60	50	39	21	35	108

[a]Sat = Volumetric water content at saturation; [b]FC = Field capacity; [c]PWP = Permanent wilting point; [d]Ksat = Saturated hydraulic conductivity; [e]TAW = Total available water.

2.4.5 Observations

Above ground destructive sampling was conducted every fortnight and then plants were oven dried at 80°C until there were no changes in total above aground biomass observed to determine accumulation of above ground biomass. Leaf area index (LAI), which is the one–sided green leaf area per unit ground surface area occupied by the plant was routinely measured using the LAI-2200C Plant Canopy Analyzer (LICOR, USA). Leaf area index, values then were converted to CC using the formula by Hsiao et al. (2012);

$$CC = 1.005 \times [1 - \exp(-0.6\ LAI)]^{1.2} \qquad \textbf{Equation 3}$$

Observed CC data and above ground biomass were used to create field observation files (.OBS) for each water treatment and experimental site.

Crop ET was calculated under field conditions as the residual of a modified soil water balance (Allen et al., 1998);

$$ET = ER + I \pm \Delta SWC, \qquad \textbf{Equation 4}$$

where;

ET = evapotranspiration,

ER = Effective rainfall (mm) is monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to runoff and deep percolation (USDA-SCS, 1967),

I = irrigation (mm), and

ΔSWC = changes in soil water content (mm) measured using a PR2/6 soil moisture probe (Delta T, UK).

At harvest, six representative plants were harvested from each plot and air dried for determination of total biomass and yield.

2.5 Simulation procedure

AquaCrop version 5.0 (FAO, 2015) was used. The created files (.CLI, .CRO, .SOL, .IRR, .MAN and .OBS) were input into AquaCrop. The model was run in thermal time (growing degree days). Simulation periods were linked to the growing cycle (day one after sowing to maturity; planting dates are given in Table 1). At Ukulinga, during 2015/16 initial soil water content was assumed to be at field capacity as planting followed a rainfall event and irrigation was applied soon after planting. During 2016/17 initial soil water content was 50% of TAW at Ukulinga, 42% of TAW at Umbumbulu and 55% of TAW at Fountainhill.

2.6 Model evaluation statistics

To evaluate model performance, statistical indicators used were correlation of determination (R^2), root mean square error (RMSE), normalised root mean square error (NRMSEcv), Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (d) (FAO, 2015). Because the different indicators have different strengths and weaknesses, an ensemble is necessary to sufficiently assess the performance of the model (FAO, 2015). Description and calculation of the different indicators can be obtained from Willmott et al. (1985) and FAO (2015).

Correlation of determination measures the strength of the association between observed and simulated values. It represents the data that is closest to the line of best fit. Values range from 0 to 1 with 1 indicating a perfect fit. Due to small number of observed values ($n < 10$), values of $R^2 > 0.90$ were considered as very good, while values between 0.70 and 0.90 were considered good. Values between 0.50 and 0.70 were considered moderately good. Values less than 0.50 were considered poor. Root mean square error measures the average magnitude of the difference between simulated and observed data. It ranges from 0 to positive infinity, and expressed in the units of the studied variable. A RMSE approaching 0 indicates good model performance. Normalized RMSE on the other hand gives an indication of the relative difference between simulated and observed values. It is expressed as a % with < 10% being very good and > 25% being poor. The Nash-Sutcliffe EF model determines the relative magnitude of the residual variance compared to the variance of the observations. An EF of 1 indicates a perfect match between the model and the observations. An EF of 0 means that the model predictions are as accurate as the average of the observed data. A negative EF implies that the mean of the observations gives a better prediction than the model. In this study, EF less than 0.4 was considered poor (FAO 2015). The Willmott's index of agreement measures the degree to which the observed data are approached by the predicted data. It ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between simulated and observed data. D -index was acceptable when it was above 0.64 (FAO, 2015). Overall model performance was considered good when at least any 3 of the 5 model evaluation indicators were good to very good.

The final biomass, ET and yield differences were computed as percentage relative differences obtained using the formula;

$$[(\text{Simulated} - \text{Observed})/\text{Observed}] \times 100\%. \qquad \textbf{Equation 5}$$

Relative differences of ± 10% were considered accurate (Farahani et al., 2009; Steduto et al., 2009) while differences of ± 20% were acceptable.

3. Results and Discussion

3.1 Groundnut

3.1.1 Calibration

For groundnut, model evaluation indicators showed that there was a good match (R^2 = 0.84 – 0.98; RMSE = 4.8 – 7.4%; NRMSEcv = 8.8 – 12%; EF = 0.80 – 0.96; d-index = 0.94 – 0.99) between observed and simulated values. However, the model underestimated CC between 60 and 120 days after planting (DAP) (period of maximum CC). Karunaratne et al. (2011) also reported similar outputs for their calibration and validation of bambara groundnut. This study used a bambara groundnut file as a template for calibration of groundnut as they are relatively similar grain legumes. In groundnut, node production may continue up to maturity, given optimum conditions (phyllochron and water availability) (Halilou et al., 2016). AquaCrop does not consider leaf appearance rate and phyllochron; this may explain the underestimation of simulated values. Groundnut could have increased leaf appearance rate in response to favourable environmental conditions during that period which was not captured by the model. Despite AquaCrop's approach of exponential growth and decay of canopy development followed by maximum CC, it was still able to simulate CC satisfactorily. This confirms AquaCrop's simplicity yet maintaining accuracy.

For biomass, model calibration of groundnut showed a moderately good match under OI (R^2 = 0.96; RMSE = 0.903 tonne ha^{-1}; NRMSEcv = 31.3%; EF = 0.9; d-index = 0.98) and a good fit under DI (R^2 = 0.98; RMSE = 0.798 tonne ha^{-1}; NRMSEcv = 21.7 %; EF = 0.95; d-index = 0.99) and RF treatments (R^2 = 0.98; RMSE = 0.650 tonne ha^{-1}; NRMSEcv = 16.7 %; EF = 0.96; d-index = 0.94) (Fig 2). Under OI, NRMSEcv was poor (31.3%); this was because the OI trials were attacked by monkeys during the later growth stages. AquaCrop does not consider damage from animals hence the model overestimated. Thus, in this instance, simulated values could be assumed to be representative of crop potential. The model simulated biomass under DI and RF relatively well. Although all the statistical indicators showed a good fit under

DI and RF, the model tended to underestimate biomass. This could be a carry-over effect from underestimation of CC. Biomass is used to simulate yield by means of a HI. Under OI, grain yield was overestimated by 48%. This was due to yield loss to monkeys. Under DI and RF, AquaCrop under- and overestimated grain yield by 0.8% and 2.2%, respectively, thus the model simulated yield accurately (Farahani et al., 2009) (Table 4). Since AquaCrop accurately simulated CC, biomass and yield under DI and RF, it can be inferred that it is a suitable model for simulating biomass and yield of groundnut under different water regimes.

The model overestimated final ET by 28% in the OI treatment, 35% in the DI treatment and 34% in the RF treatment (Table 4). One of the distinguishing features of AquaCrop is the separation of ET into evaporation (E_s) and transpiration (T_r) based on a simple CC model (Vanuytrecht et al., 2014). It would be assumed that since the model underestimated CC, which is proportional to $T_{r,}$ (***cf.*** section 2.1) then E_s would be the parameter overestimated. Based on RMSE values, there was more underestimation of CC under RF relative to DI and OI. To support the assumption, it was expected that results of simulated E_s relative to T_r under the different water regimes show that there was more E_s relative to T_r under rainfed conditions. This was however not the case as proportion of E_s was the same under all the watering regimes. This shows that the model tended to overestimate both E_s and T_r and this was greater under DI and RF conditions. It is not clear why the model overestimated ET.

3.1.2 Testing

At Ukulinga, model performance evaluators showed moderately good to poor model performance in simulating CC across all the water regimes (Fig 3). Under OI, R^2 was moderately good (0.75) while it was very good under DI and RF conditions (0.92 and 0.93, respectively). D-index was good across all the water regimes (0.70; 0.78 and 0.84, in the OI, DI and RF treatment respectively). Root mean square error, NRMSEcv and EF were poor across all the water regimes (> 8.6%, > 43.8% and < -0.38, respectively) (Fig 3). The coefficient of determination and d–index showed moderately good fit as they are not sensitive to the magnitude of the difference between simulated and observed data. Root mean square error, NRMSEcv and EF were very poor due to their sensitivity to magnitude of the difference between simulated and observed data (***cf.*** section 2.6).

The model overestimated CC for groundnut across all the watering regimes. This was mainly as a result of disturbances in our trials by monkeys and wild pigs which could not be factored into the model. The canopy was often disturbed as the monkeys were seeking for the groundnut pods. As the canopy was damaged, it would take time to recover which was also not factored into the model. This was evident in the differences between observed and estimated time to maturity (29 May 2017 and 18 May 2017, respectively). While crop damage by pests and animals is a reality in farming, incorporating this in crop growth models remains a challenge (Donatelli et al., 2017). Incorporating damage by animals into crop models is often challenging due to differences in patterns of damages and lack of data on extent of damage (Bayani et al., 2016). This is partly because of lack of proper methods to estimate animal damage.

Consistent to results of CC, overall model performance was poor for groundnut cumulative biomass (Fig 4). Similar to CC R^2 (OI = 0.96; DI = 0.96; RF = 0.85) and d-index values (OI = 0.49; DI = 0.63; RF = 0.81) showed poor to very good fit, while RMSE (OI = 2.449 tonne ha^{-1}; DI = 1.889 tonne ha^{-1}; RF = 1.024 tonne ha^{-1}), NRMSEcv (OI = 299.1%; DI = 207.7%; RF = 93.5%) and EF (OI =14.21; DI = -5.10; RF = -0.56) were very poor. Cumulative biomass was also overestimated due to animal attacks. Consequently, final biomass was overestimated by 61, 59 and 52% in the OI, DI and RF trials. Grain yield was overstimated by up to 86% because grain was of interest to the monkeys, hence they were mostly affected. However, the damage by monkeys did not affect estimation of final ET. Final ET was underestimated by 1.4 % in the OI treament and overestimated by 9 and 11% in the DI and RF treatments, respectively. It is most probable that the disturbances in the plant canapy would have affected the separation of ET into E_s and T_r, which the study did not quantify.

The model was further tested for its performance at different sites (Fountainhill and Umbumbulu) under rainfed conditions. For Fountainhill, overall model simulation of CC was good (R^2 = 0.82; RMSE = 11.5%; EF = 0.69; d-index = 0.94) although NRMSEcv showed moderately poor performance (26.8%) (Fig 5). This could be because the model failed to capture canopy senesence and crop maturity of the crop. This could be as a result of the initial soil water conditions at Fountanhill. At planting, initial soil water content was 55% of TAW. The model overestimated the delay in crop establishment. Initial values of CC showed that the model underestimated CC (Fig 5) during crop development as a result of delayed timing of crop establishment. As a result the model delayed time to senescence and time to maturity, leading to poor simulation of CC towards the end of the season. Steduto et al. (2009) reported on the sensitivity of the model to initial soil water conditions. This could be because the model only considers time to emergence under optimal conditions and does not consider the soil water upper and lower thresholds for emergence of different crops.

For biomass accumulation, model performance for Fountainhill was good to very good (R^2 = 0.98; RMSE = 0.540 tonne ha^{-1}; NRMSEcv = 18.5%; EF = 0.9; d-index = 0.99). The model underestimated biomass which could be as a result of carry over effect from CC overestimating time to crop establishment. Interestily, final biomass was overestimated by 18% despite underestimation of cumulative biomass (Table 4). The reason for this overestimation is not clear. Grain yield and ET were underestimated and overestimated by 14 and 11%, respectively which was considered acceptible (Table 4). Despite the slightly poor NRMSEcv for CC (26.5%), the model perfomed well for Fountaihill.

For Umbumbulu, the model performed well in simulating both CC and cumulative biomass (R^2 = 0.98 and 1, respectively; RMSE = 3.5% and 0.25 tonne ha^{-1}, respectively; NRMSEcv = 8.4 and 11.2%, respectively, EF = 0.98 for both; d -index = 1 for both) (Fig 6). Consequently, only 2% underestimation of final biomass was observed which was accurate (Faharani et al., 2009). Despite the good simulation of CC and biomass, the model poorly overestimated both final grain yield and ET (34%) (Table 4). The model simulated increase in HI of ≈ 5%. Umbumbulu was chracterised as extremely hot during that season. According to Vara Prasad et al. (1999, 2000) the threshold day temperature for pollen production and viability for groundnut was 34°C. The model was set to consider 34°C as the threshold for pollination. Temperature data showed that during groundnut reproductive stage there were 12 days above 34°C. However, during the runs it could not be established if the model had captured pollination affected by heat stress and to what magnitude. Model output showed that HI had increased 5% and it was not clear which adjustments had been factored in. Without clear indication on the adjustments of HI, it could not be established why the model overestimated grain yield.

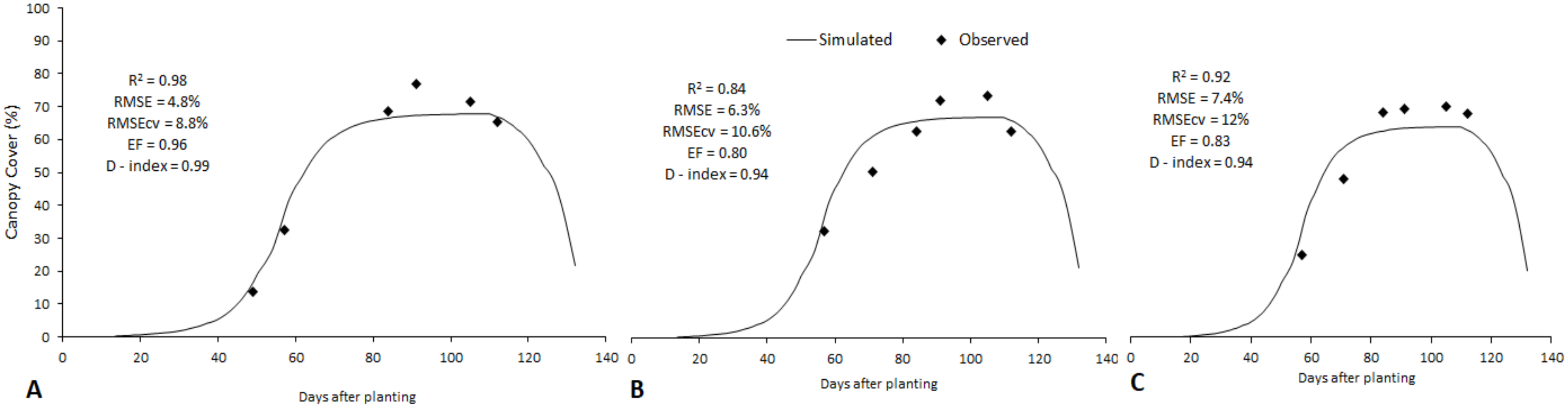

Figure 1: Simulated and observed CC for groundnut under A) optimum irrigation B) deficit irrigation C) rainfed conditions during the calibration season 2015/16.

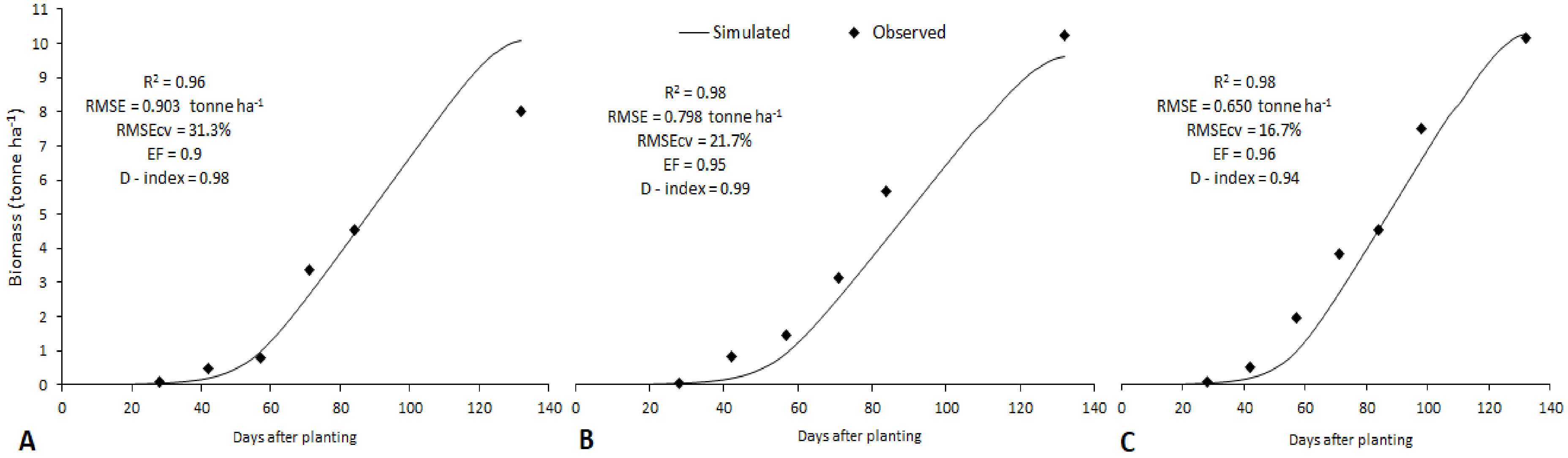

Figure 2: Simulated and observed cumulative biomass for groundnut under A) optimum irrigation B) deficit irrigation C) rainfed conditions during the calibration season 2015/16.

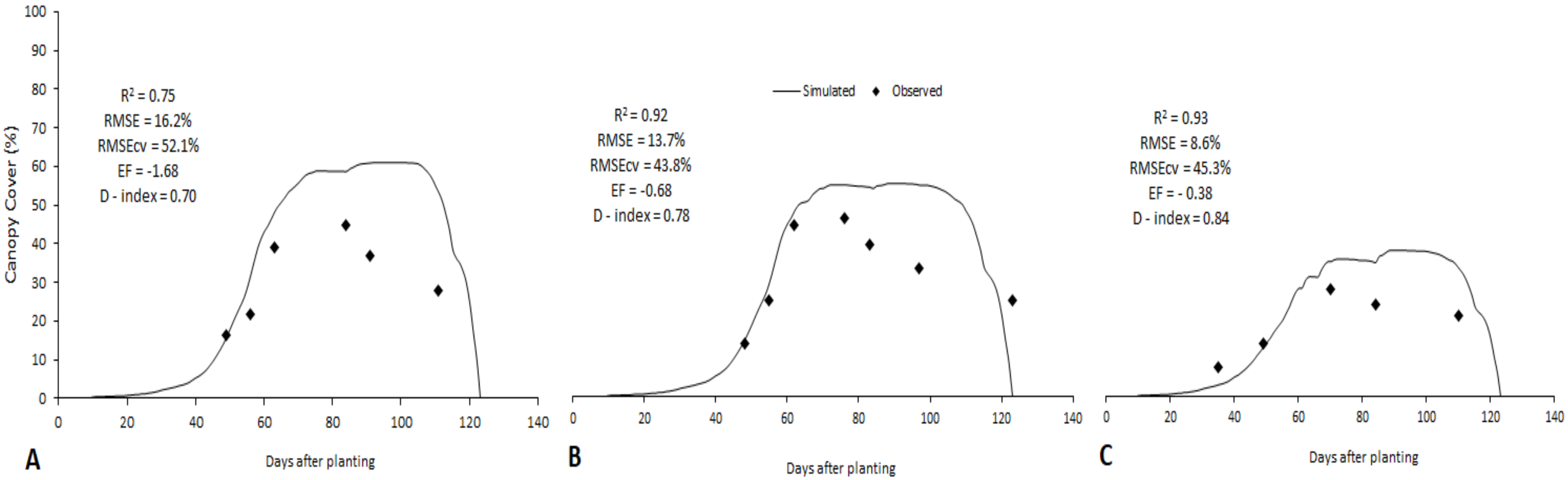

Figure 3: Simulated and observed CC for groundnut under A) optimum irrigation B) deficit irrigation C) rainfed conditions during model testing at Ukulinga (2016/17 season).

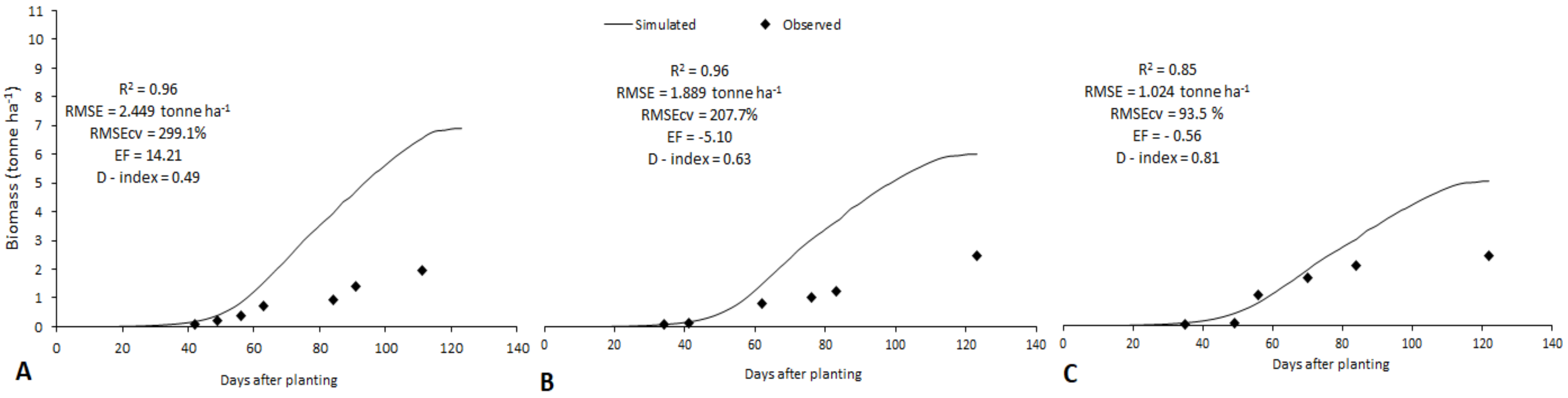

Figure 4: Simulated and observed cumulative biomass for groundnut under A) optimum irrigation B) deficit irrigation C) rainfed conditions during model testing at Ukulinga (2016/17 season).

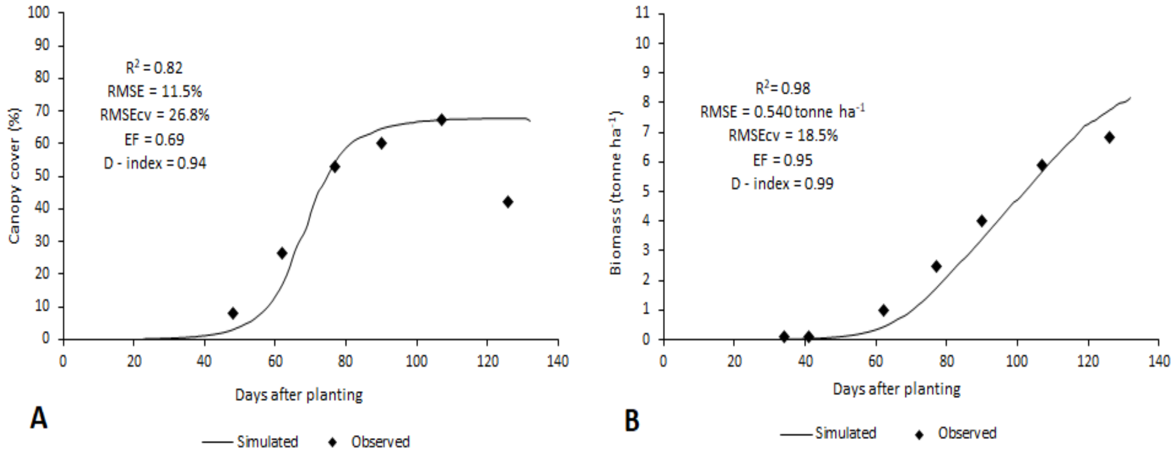

Figure 5: Simulated and observed CC (A) and cumulative biomass (B) for groundnut at Fountainhill during model testing (2016/17 season).

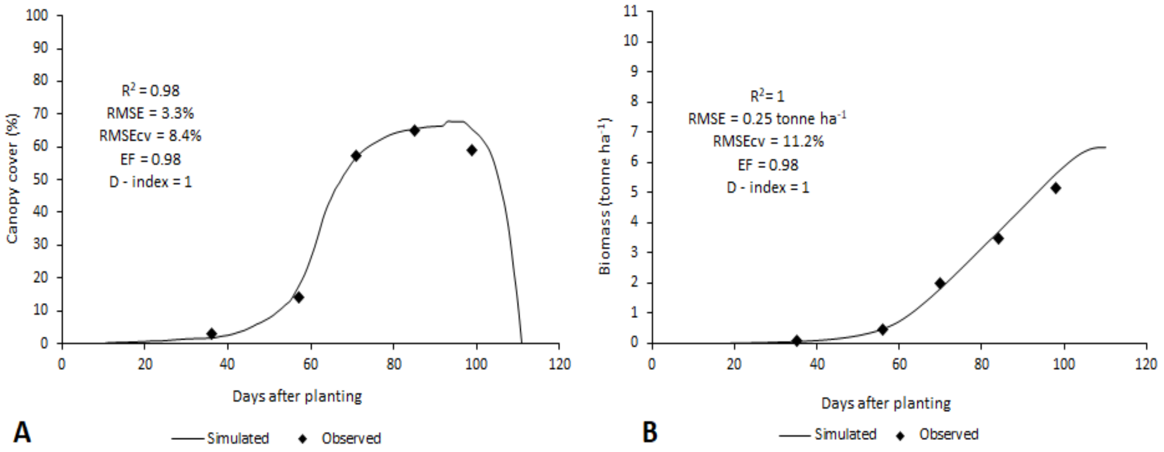

Figure 6: Simulated and observed CC (A) and cumulative biomass (B) for groundnut at Umbumbulu during model testing (2016/17 season).

Table 4: Simulated and observed grain yield and evapotranspiration (ET) for groundnut during model calibration and testing at Ukulinga, Fountainhill and Umbumbulu.

		Final Biomass			**Final Grain yield**			**Final ET**		
		Simulated	Observed	Difference	Simulated	Observed	Difference	Simulated	Observed	Difference
		tonne ha^{-1}		%	tonne ha^{-1}		%	mm		%
Calibration	OI	10.068	8.020	20.3	2.885	1.950	47.94	406	316	28.48
	DI	9.929	10.540	- 6	2.874	2.900	- 0.89	397	292	35.95
	RF	9.788	9.550	2	2.833	2.770	2.27	380	283	34.27
Testing	OI	6.895	2.681	61.11	1.328	0.585	55.94	340	345	-1.47
	DI	5.768	2.359	59.10	1.712	0.362	78.85	308	280	9.09
	RF	4.475	2.148	52	2.046	0.267	86.95	282	249	11.70
	Fountainhill	8.439	6.855	18.77	2.088	2.387	-14.31	323	287	11.14
	Umbumbulu	6.491	6.669	-2.74	1.858	1.213	34.71	357	234	34.45

3.2 Dry Bean

3.2.1 Calibration

For dry bean, model calibration showed very good to moderately good fit between observed and estimated values of CC under OI (R^2 = 0.88; RMSE = 6.8%; NRMSEcv = 14.8%, EF = 0.84; d-index = 0.96), DI (R^2 = 0.96; RMSE = 6.7%; NRMSEcv = 14%, EF = 0.85; d-index = 0.95) and RF (R^2 = 0.90; RMSE = 6.5%; NRMSEcv = 16.1%, EF = 0.76; d-index = 0.95) (Fig 7). Under RF, the model overestimated CC during crop midseason (30 – 75 DAP) while under OI and RF the overestimation of CC was limited to period of crop development (40 – 60 DAP). This was as result of erratic establishment that was experienced in the field, which was then gap-filled to meet the desired plant population. This caused an uneven plant stand. Under OI and DI, the plants that were planted during gap-filling developed fast due to irrigation and hence the model only underestimated CC up to 60 DAP. In the RF treatment due to the effect of the gap-filling canopy was uneven for up to 75 DAP due to limited water availability.

Model evaluation statistics for cumulative biomass showed very good match between observed and simulated values in the OI (R^2 = 0.98; RMSE = 0.228 tonne ha^{-1}; NRMSEcv = 7.7%, EF = 0.98; d-index = 1) and RF (R^2 = 0.98; RMSE = 0.381 tonne ha^{-1}; NRMSEcv = 13.7%, EF = 0.96; d-index = 0.99) (Fig 8). For the DI treatment, RMSE and NRMSEcv were moderately good (0.454 tonne ha^{-1} and 16.2%, respectively) while R^2, EF and d-index were very good (0.96, 0.90 and 0.98, respectively). Similar to groundnut, monkeys attacked the trial towards the end of the season. For groundnut, the animal attacks were in the fully irrigated trial while for dry bean the DI treatment was affected. Consequently, the model overestimated final biomass in the DI by 15%. In the OI treatment the model was more accurate, only underestimating biomass by 1.6%. In the RF treatment, results of CC were confirmed by biomass where the model also overestimated biomass from planting. Thereafter, the model underestimated biomass (Fig 8). The model hastened canopy senescence under RF conditions relative to the field trials. This led to overestimation of biomass by 14% which was in the acceptable range (± 20%). For final grain yield, results were inverse to final biomass — yield was accurately estimated in the RF treatment (-0.1%) while in the OI the estimation was acceptable (-14%). True to expectation, final grain yield was overestimated by 28% in the DI treatment, due to yield losses to monkeys. The model overestimated ET by 21% in the OI to 28% in the DI treatment. This was consistent with results of groundnut where the model also overestimated ET by $\approx$ 30%.

3.2.2 Testing

At Ukulinga, model performance evaluators showed that overall model performance was moderately good to poor in simulating canopy under OI (R^2 = 0.77; RMSE = 8.11%; NRMSEcv = 38.5%; EF = 0.20; d-index = 0.85). Although R^2 and d-index were good (0.77 and 0.85, respectively) the criteria was that overall model performance was good when at least three of the statistical indicators were at least moderately good (***cf***. section 2.6). Under DI and RF model performance was very good to moderately good (R^2 = 0.9 for both; RMSE = 4.9 and 9.2%, respectively; NRMSEcv = 16.2 and 22.6%, respectively; EF = 0.89 and 0.98, respectively; d-index = 0.98 and 0.92, respectively) (Fig 9). The model overestimated biomass. However, based on observed values, the OI developed in an unpredicted manner with a relatively smaller canopy compared to the DI and RF, despite that it was optimally irrigated. It was not clear during the trials why the plants in the OI were poorly developing as all trials were optimally fertilised and kept disease and weed free.

For cumulative biomass, the same trends as the one for CC were observed – the model was very good to poor under OI (R^2 = 0.96; RMSE = 0.455; NRMSEcv = 52.9%; EF = 0.74; d-index = 0.95) and very good to moderately good under DI (R^2 = 0.98; RMSE = 0.275; NRMSEcv = 21.1%; EF = 0.93; d-index = 0.98) and RF (R^2 = 0.98; RMSE = 0.391; NRMSEcv = 14.1%; EF = 0.96; d-index = 0.99) (Fig 10). However, under OI, overall model performance was considered good because three of the statistical indicators (R^2, EF and d-index) were very good. Despite the high NRMSEcv for biomass accumulation, the final estimation of biomass under OI was acceptable (18.7%). Under DI and RF, the model was more accurate in estimating final biomass (-1.7 and -5.8%, respectively). Grain yield was accurately estimated under OI and DI (+6 and +2%, respectively) while it was poorly estimated under RF (26%). During calibration, the model overestimated ET by 21 – 28% and this was slightly higher during model testing (32 – 38%).

For Fountainhill, overall model performance for simulation of dry bean CC was moderately good (R^2 = 0.98; RMSE = 9.1%; NRMSEcv = 23%; EF = 0.48; d-index = 0.86) (Fig 11). For cumulative biomass, overall model performance was moderately good to poor (R^2 = 0.68; RMSE = 1.496 tonne ha^{-1}; NRMSEcv = 53.7%; EF = 0.6; d-index = 0.84) (Fig 11). Based on the criteria for overall model performance (***cf.*** section 2.6), overall model performance was acceptable for cumulative biomass despite the poor RMSE and NRMSEcv (1.496 tonne ha^{-1} and 53.7%, respectively) (Fig 11). The model overestimated both CC throughout the whole season while biomass was only overestimated towards the end of the season. For groundnut, it was observed that the model overestimated delay in crop establishment (***cf.*** section 3.1.2). For dry bean, the model simulated earlier establishment relative to observed. This led to overestimation of CC by the model throughout the season. This further highlights the issue of sensitivity of different crops to initial soil water content which is not factored into the model. Grain yield was accurately estimated (+9%) and estimation of final ET was acceptable (+18%) (Table 5).

For Umbumbulu, model performance for simulating CC and biomass of dry bean was moderately good to poor (R^2 = 0.92 and 0.98, respectively; RMSE = 11.9% and 0.101 tonne ha^{-1}, respectively; NRMSEcv = 71.2 and 30.1%, respectively; EF = -1.43 and 0.78 respectively; d-index = 0.60 and 0.98, respectively) (Fig 12). For cumulative biomass, overall model performance was acceptable despite poor NRMSEcv (30.1%). The model underestimated CC throughout the season. Model output showed this was mostly due to canopy expansion stress because of water stress. The model estimated an acceptable final biomass (+12.6%). The model simulated no grain yield although grain yield of 0.285 tonne ha^{-1} was observed. This could be because the model simulated insufficient required for yield formation. Final ET was overestimated by 27% (Table 5).

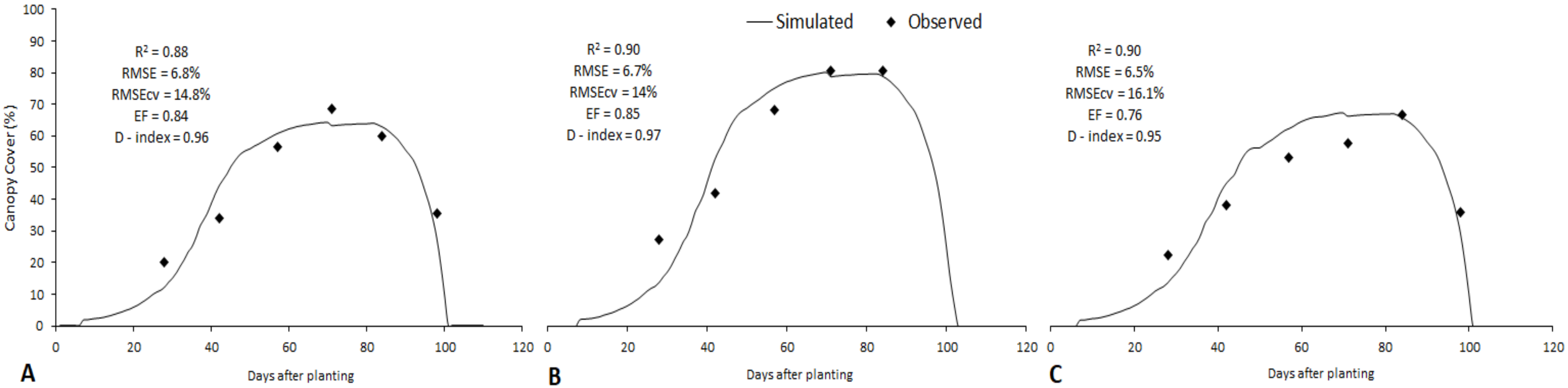

Figure 7: Simulated and observed CC for dry bean under A) optimum irrigation B) deficit irrigation C) rainfed conditions during the calibration season 2015/16.

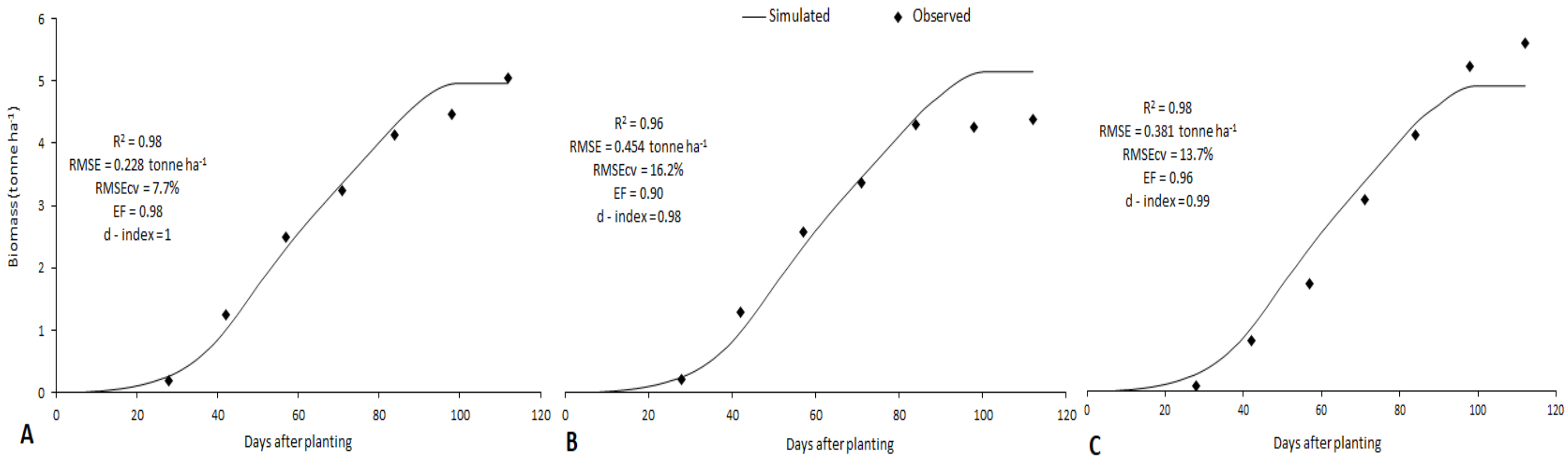

Figure 8: Simulated and observed cumulative biomass for dry bean under A) optimum irrigation B) deficit irrigation C) rainfed conditions during the calibration season 2015/16.

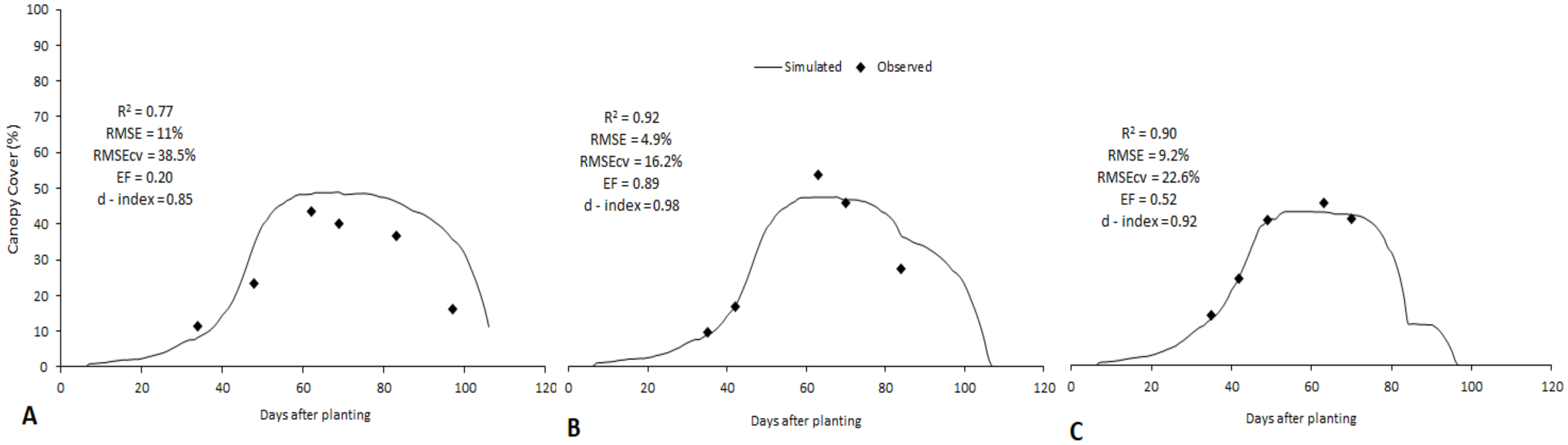

Figure 9: Simulated and observed CC for dry bean under A) optimum irrigation B) deficit irrigation C) rainfed conditions during model testing at Ukulinga (2016/17 season).

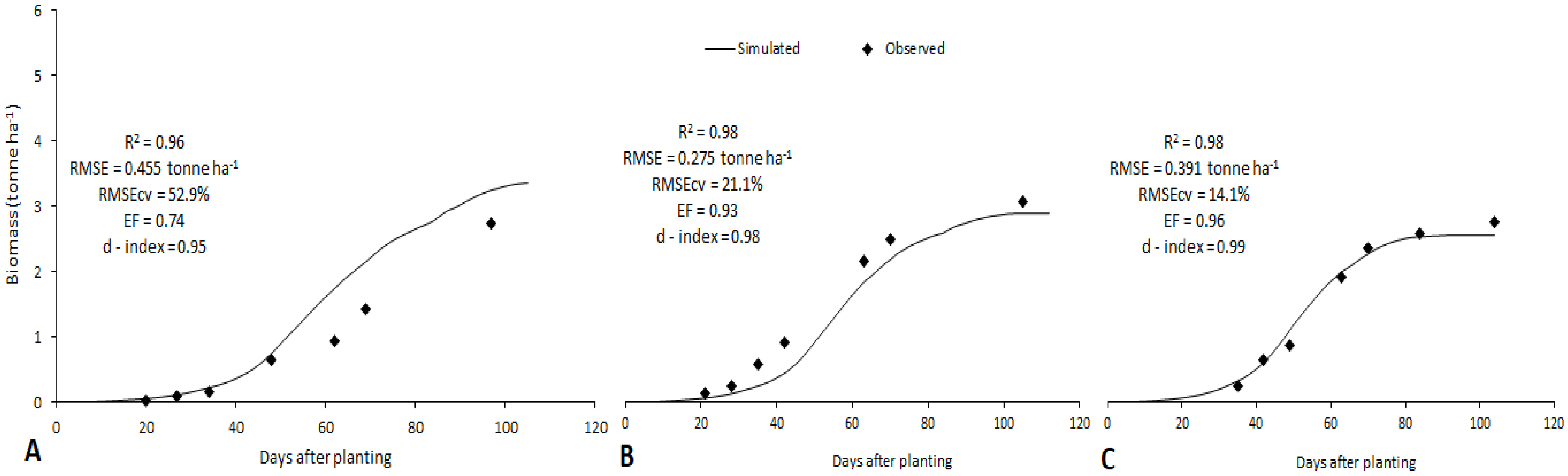

Figure 10: Simulated and observed cumulative biomass for dry bean under A) optimum irrigation B) deficit irrigation C) rainfed conditions during model testing at Ukulinga (2016/17 season).

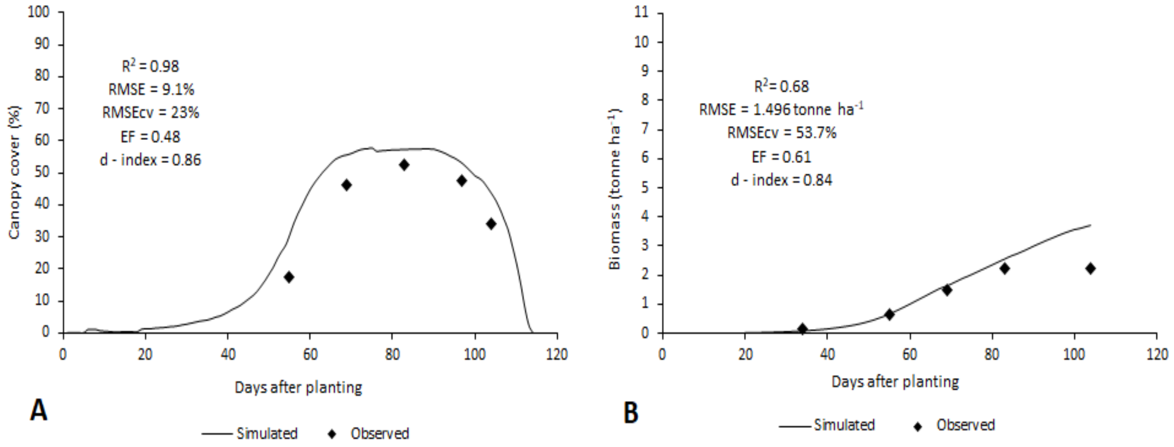

Figure 11: Simulated and observed CC (A) and cumulative biomass (B) canopy for dry bean at Fountainhill during model testing (2016/17 season).

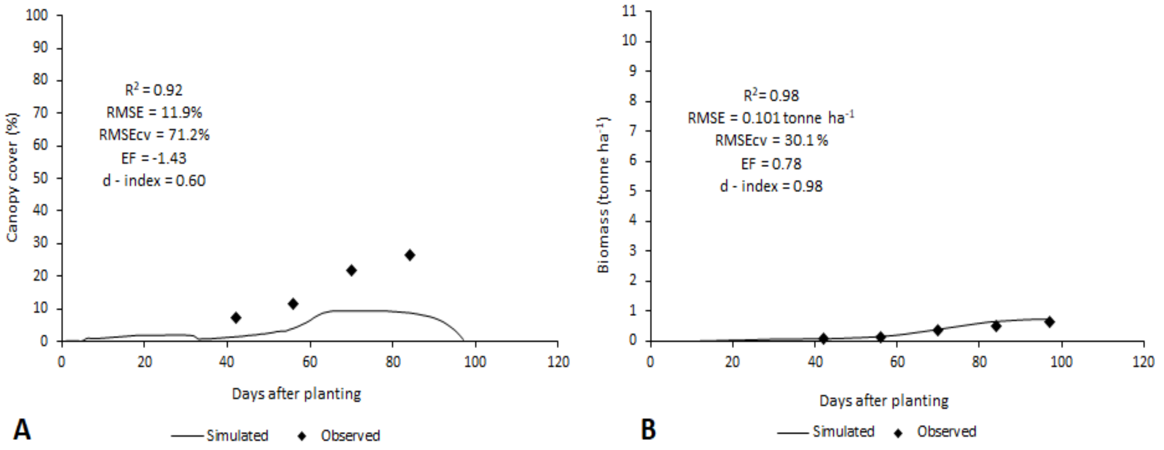

Figure 12*:* Simulated and observed CC (A) and cumulative biomass (B) for dry bean at Umbumbulu during model testing (2016/17 season).

Table 5: Simulated and observed grain yield and evapotranspiration (ET) for dry bean during calibration and testing at three different sites (Ukulinga, Fountainhill and Umbumbulu).

		Final Biomass			**Final Grain yield**			**Final ET**		
		Simulated	Observed	Difference	Simulated	Observed	Difference	Simulated	Observed	Difference
		tonne ha^{-1}		%	tonne ha^{-1}		%	mm		%
Calibration	OI	4.956	5.040	-1.6	1.953	2.260	-15.7	340	268	21.1
	DI	4.980	4.222	15.2	1.968	1.400	28.8	333	239	28.2
	RF	4.625	5.280	-14.1	1.957	1.960	- 0.1	320	238	25.6
Testing	OI	3.359	2.730	18.7	1.385	1.296	6.4	290	195	32.75
	DI	2.860	2.911	-1.7	1.122	1.098	2.1	263	163	38.02
	RF	2.402	2.543	-5.8	0.856	1.081	- 26.8	233	143	38.62
	Fountainhill	3.877	2.219	42.7	1.435	1.302	9.1	262	214	18.32
	Umbumbulu	0.746	0.652	12.6	0	0.282	-	286	208	27.27

3.3 Conclusion

During calibration the model simulated CC and cumulative biomass well for both crops. The model tended to underestimate CC of groundnut during maximum canopy cover. This was attributed to leaf appearance rate and phyllochron. For groundnut, final biomass was overestimated in the OI while for dry bean final biomass was overestimated in the DI. This was due to monkey attacks towards the end of the season. For both crops, the model overestimated ET. During model testing for groundnut, model performance was poor for CC and cumulative biomass. The model overestimated CC and cumulative biomass for groundnut across all the water regimes. This was mainly because of disturbances in our trials by monkeys and wild pigs which could not be factored into the model. Consequently, final biomass and grain yield were overestimated. The model accurately estimated final ET. The model was further tested for two environments (Umbumbulu and Fountainhill) where it simulated CC and biomass well. At Umbumbulu, however, the model overestimated grain yield and ET. For dry bean testing, the model performed well under DI and RF. For Fountainhill, overall model performance for simulating CC and biomass was acceptable. Grain yield was accurately simulated. For Umbumbulu, the model poorly simulated CC. Biomass simulation was acceptable while ET was overestimated. Overall the model showed potential for simulating yield and ET of groundnut and dry bean under semi-arid conditions. There is need to improve model parameters for both dry bean and groundnut before the model can be applied for different soils and climates.

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CHAPTER 7

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The semi- and arid tropics [Sub-Saharan Africa (SSA) and south Asia (SA)] are currently suffering from high prevalence of malnutrition (IFPRI, 2016). Crop production is biased towards staple crops, which has resulted protein and micronutrients deficiencies in diets, especially of poor rural people. There is need to increase dietary diversity to improve dietary quality and alleviate malnutrition. Grain legumes are rich sources of protein and micronutrients but remain under-explored. There is need to reintroduce neglected underutilised grain legumes to diversify crop production and increase resilience. These may be ideal for the semi- and arid tropics, where water scarcity and poor soil fertility limit agriculture. The promotion of legumes, especially underutilised legumes, will requires knowledge on their water use (ET), adaptation to environments and nutritional value. this alludes to the need for a water-food-nutrition-health nexus. This entails use of metrics that incorporate ET, yield and nutrition such as nutritional water productivity (NWP).

In this study, it was hypothesised that there are no differences between major and underutilised grain legumes with respect to adaptation, yield, productivity, nutritional content and nutritional water productivity. The major legumes selected for the study were groundnut and dry bean. Two *Vigna* species were selected to represent underutilised grain legumes [bambara groundnut (*Vigna subterranea*) and cowpea (*Vigna unguiculata*)]. To test this hypothesis, field experiments were conducted under varying water regimes and environmental conditions. Results from the field experiments were then used to calibrate and test the AquaCrop model for groundnut and dry bean.

7.2 General Discussion

7.2.1 *Value of grain legumes*

At the onset, a critical state-of-the-art literature review (Chapter 2) was undertaken to identify opportunities and challenges for successful promotion of grain legumes along the value chain. The review showed that research on grain legumes has mainly focused on a few major grain legumes based on economic value. This has inadvertently led to neglect of other grain legumes. With issues of crop diversification and dietary diversity, lies an opportunity to reintroduce underutilised grain legumes and tap into their potential. However, currently there is limited documented information on these crops, which may limit their promotion. There is need for more research, development and innovation on these crops to improve their attractiveness to farmers and consumers as well as to increase competitive advantage with the major grain legumes.

From an environmental perspective, grain legumes have the potential to improve soil fertility status. According to Tittonell et al. (2005), soil fertility in the semi- and arid tropics is decreasing with nitrogen being one of the major deficient nutrients. Grain legumes have a unique ability to biologically fix nitrogen, making them ideal for sustainable agriculture. Biological nitrogen fixation, allows for reduced use of fertilisers, consequently lowering greenhouse gas emissions. Legumes have also been associated with increase in soil C/N ratio, thus increasing soil organic matter (Stagnari et al., 2017).

Grain legumes are also important crops for human nutrition and health. Major forms of malnutrition in the semi- and arid tropics are because of lack of a balanced diet, lack of protein, iron, vitamin A, calcium and zinc. Legumes contain appreciable amounts of these nutrients, enough to cover more than 50% of recommended dietary allowance. Grain legumes have also been shown to reduce the occurrence of a condition called environmental enteric dysfunction (EED), which is common among the rural poor in SSA and SA. While the review focused on nutritional value of grain legumes from a human perspective, their value as animal feed was also established. Another advantage of grain legumes highlighted by the literature review was their long shelf-life, hence availability throughout the year. This offers a more sustainable protein source.

The novelty of the review (Chapter 2) was in the use of a research value chain approach in identifying opportunities and challenges for promotion of grain legumes. The review concluded that currently the research value chain of legumes is poorly developed and understood. Aspects of grain legume breeding, seed systems, production, marketing and utilization are not well-developed. Focusing on completing knowledge gaps within the value chain could aid in the promotion of grain legumes in semi- and arid tropics.

7.2.3 Effect of irrigation on yield of grain legumes (Chapter 3)

The 2015/16 season was characterised by El Niño that caused significant yield losses (≈ 70%) in Southern Africa (Archer et al., 2017). During the season, 435 mm of rainfall were received, and we observed grain yields of ≈ 2 000 kg ha^{-1} for dry bean, 2700 kg ha^{-1} for groundnut and 1500 kg ha^{-1} for bambara groundnut. These yields were comparable and relatively higher compared to those observed elsewhere in the literature. During 2016/17 seasons, trials were planted late on the 16th of January 2017. There were several attempts to plant prior to this, which failed due to monkey attacks. It was also suspected that monkeys became problematic during 2016/17 as the previous year was a drought and there was not much food in the reserves and the wild. During 2016/17, only 235 mm of rainfall was observed as the trial was planted late during the summer season. Late planting created heterogeneity between the two seasons. Yield of groundnut and bambara groundnut reduced drastically (by over 100%) during 2016/17, a result that was attributed to the late planting and several disturbances by monkeys during the trial, which led to poor canopy development and yield losses. However, the trends in results on effect of water regimes on yield and yield components were the same during both seasons (results were not significantly between water regimes). It was surprising that water added through supplementary irrigation did not significantly improve yield. The varieties used in the study were selected based on adaptability to rural cropping systems and could be partly why they were well-adapted under deficit and rainfed production. Evapotranspiration decreased under rainfed and deficit irrigation conditions, relative to the optimum irrigation treatment. The decrease in ET under rainfed and deficit irrigation conditions did not result in yield decreases. This led to improved water productivity under rainfed and deficit irrigation conditions relative to optimum irrigation conditions.

During both seasons, crops exhibited drought avoidance strategies in response to water stress. To respond to declining soil water availability, crops regulated stomatal conductance to minimize water loss through transpiration. Canopy expansion was also regulated under limited soil water availability as a strategy to minimize surface area available for transpiration and minimize water loss. The grain legumes under study also exhibited drought escape through hastening of key phenological stages (flowering, podding and maturity) under rainfed and deficit irrigation conditions. These strategies show suitability of grain legumes for water limited areas.

The study went further to determine crop characteristics that were desirable and that contributed to conserved ET and high grain yield. Undesirable crop characteristics were also identified to determine interventions on how the crops can be improved. Groundnut had high stomatal conductance which was matched by high ET and biomass. Groundnut flowered early and was indeterminate which also contributed to high grain yield. Dry bean was early maturing, which resulted in low ET. Early maturity was also a positive attribute during 2016/17 where planting was late, as the crop matured before the onset of cold autumn temperatures. Dry bean had a significantly higher HI. In the case of bambara groundnut, it was observed that the landrace had lower stomatal conductance relative to the other grain legumes. This indicates conserved transpiration ET an attribute that can associated with their natural adaptation to limited water availability. However, this positive attribute was masked by the poor canopy development of bambara groundnut that led to significant unproductive ET through soil evaporation. Bambara groundnut also emerged, flowered and podded late, a characteristic that was associated with its low HI and low grain yield.

This study was a first to benchmark underutilised grain legumes to major grain legumes under similar conditions. It was observed that the major grain legumes had higher yield compared to bambara groundnut. In this study, bambara groundnut showed attributes that were not favourable for farmers. Major legumes were also well-adapted relative to bambara groundnut. Any successful promotion of underutilised crops should be preceded by crop improvement for the crops to be accepted by farmers. The study highlighted areas of improvement for bambara groundnut (improved canopy development, yield and harvest index), which could act as a starting point for breeders.

7.2.3 Adaptation of grain legumes across environments (Chapter 4)

Grain legumes have been associated with poor and unstable yields across environments. Yield has been shown to vary significantly among species, and has exhibited low and high extremes under different environments (Cernay et al., 2016). Findings of Chapter 4 (Adaptation and productivity of selected grain legumes in contrasting environments of KwaZulu-Natal, South Africa) corroborated these findings. Environments influenced the crops’ development, yield, ET and water productivity. Sandy soils at Fountainhill had a negative effect on time to emergence. Bambara groundnut was consistently the slowest to emerge regardless of site and season. With the limited water resources and drive for improved water productivity, this is an impediment to its promotion as it decreases yield and increases unproductive ET through soil evaporation. Bambara groundnut and groundnut consistently yielded better at Fountainhill where the soil was sandy. The grain legumes showed poor tolerance to different environments and extreme weather events. Dry bean was the least performing species at Umbumbulu where it was extremely hot. While dry bean was sensitive to heat stress at Umbumbulu, it was more tolerant to low rainfall and late planting at Ukulinga during 2016/17, compared to groundnut and bambara groundnut. Results of GGE analysis showed that groundnut was the highest performing species with respect to mean yield. At Fountainhill, bambara groundnut yield was similar to groundnut. Cowpea was the least yielding crop, but it exhibited the highest yield stability across environments.

Results of Chapter 4, show that the grain legumes under study were not well-adapted to the different environments. This suggests the adoption of different crops for different environments for improved yield. This supports the idea of crop diversification as different crops are well-adapted to different environments. Over reliance on a few grain legumes could have led to neglect of grain legumes as they showed yield instability; an attribute unattractive for farmers. There is still need for a better understanding of gene × environment interaction of grain legumes. This will direct breeding for improved yield stability across environments. It was interesting to observe that at Fountainhill, bambara groundnut yield was similar to groundnut. This was evidence that bambara groundnut could have the same yield potential as groundnut but has not benefitted from crop improvement to achieve this potential. This further justifies the need for crop improvement of underutilised crops.

7.2.4 Nutrient content and nutritional water productivity (NWP) of grain legumes (Chapter 5)

A nexus approach was used to determine the combined gain of yield and nutritional content per unit of water consumed (NWP). This study was a first to determine NWP of grain legumes. Crops differed in their nutrient content. Groundnut had higher fat content relative to the other crops. Any promotion of groundnut should be accompanied with awareness on the risk associated with its over consumption (obesity). For all the grain legumes, protein content was between 205 and 325 g kg^{-1}, enough to supply 40 – 60% of protein recommended dietary allowance (RDA). The study also showed that dry bean and cowpea have the potential to supply 40 – 60% of Fe and Zn RDA. It was interesting to observe that cowpea and dry bean contained ≈500% more Zn content than leafy vegetables (Nyathi et al., 2016). This is further evidence that grain legumes have a role to play in dietary diversity. Bambara groundnut had the lowest macro– and micronutrient content; an issue that needs improvement if the crop is to be promoted for alleviation of malnutrition in semi- and arid tropics.

Nutrient content of crops differed across water treatments and environments. When rainfall was low, protein content for all the crops was also low which was attributed to reduced N mobilisation from soil to the plant. This showed that effects of water stress should not only be considered from a yield perspective but from a nutritional content as well. Iron nutrient content was associated with soil type. It was higher at Ukulinga compared to the other sites due to the good water holding capacity of clay soils at Ukulinga which enhanced iron mobility from soil to grain due to Fe^{2+}/Fe^{3+}. The study highlighted that edaphic factors also play a role in nutrient composition of grain legumes and cannot be ignored on strategies to improve nutrition in plants.

Nutritional water productivity varied significantly among the crops. With respect to fat productivity, groundnut was the most productive producing up to 400 g m^{-3}, respectively. For $NWP_{Fe,\ Zn\ and\ Ca}$, dry bean was the most productive followed by cowpea. For groundnut, despite the high grain yield, $NWP_{Fe,\ Zn\ and\ Ca}$ were low due to poor nutrient content. The major legumes (groundnut and dry bean), had the highest $NWP_{protein}$, relative to the underutilised grain legumes. In the case of groundnut, this was attributed to high protein content and high yield observed for the crop. For dry bean, high $NWP_{protein}$ was attributed to low ET and high protein content. For the underutilised grain legumes (cowpea and bambara groundnut), $NWP_{protein}$ was low due to low protein content, high ET and low grain yield for bambara groundnut and low yield for cowpea. Results of NWP further highlight the issue of crop improvement in underutilised grain legumes to improve yield as this also had negative implications on NWP. For bambara groundnut the issue of unproductive ET is also highlighted by results of low NWP (water consumed did not translate to high yield and nutritional gain).

Environments had a significant effect on NWP. This was mostly because of yield instability across environments. Fluctuations in NWP followed fluctuations in grain yield. Low grain yield caused low NWP. Low yield did not translate to decreases in ET further affecting NWP. Yield instability does not only affect food security of subsistence farmers but nutritional gain as well. Nutritional water productivity was a useful metric for quantifying the water-food-nutrition nexus.

7.2.5 Modelling yield and ET of groundnut and dry bean (Chapter 6)

The study was the first to calibrate groundnut and dry bean for the FAO AquaCrop Model. Although cowpea and bambara groundnut were part of the study, they could not be calibrated. AquaCrop has already been calibrated and tested for bambara groundnut (Mabhaudhi et al., 2014). For cowpea, the frequent animal attacks targeting cowpea and loss of yield meant that there was insufficient data to calibrate and test the model. Thus, there is a still a gap with regards to calibrating and testing AquaCrop for cowpea.

AquaCrop was calibrated for groundnut and dry bean and tested under varying water regimes and environments. The model was successfully calibrated for both crops; there was a good match between simulated and observed values. There was overestimation of final biomass in the optimum irrigation treatment for groundnut and deficit irrigation treatment of dry bean towards the end of the season as a result monkey attacks. The model also tended to overestimate ET. Model testing for groundnut was poor at Ukulinga under all the water regimes. Both canopy cover and cumulative biomass were overestimated due to the disturbances in our trials by monkeys and wild pigs, which could not be factored into the model. The model accurately estimated final ET at Ukulinga during model testing. At Fountainhill and Umbumbulu the model simulated canopy cover and biomass well although at Umbumbulu grain yield and ET were overestimated.

For dry bean testing, the model performed well under deficit irrigation and rainfed conditions at Ukulinga. At Fountainhill the model underestimated time to crop establishment leading to the model overestimating canopy cover throughout the season. However, overall model performance for simulating canopy cover, biomass, grain yield and ET was acceptable. For Umbumbulu, the model poorly simulated canopy cover while biomass simulation was acceptable. The model did not accurately simulate growth, yield and ET under all test conditions. However, the model could be useful for assessing growth, yield and ET under semi- and arid conditions. There is however need for further testing of the model under as monkey attacks limited the testing in this study. This could aid in identifying aspects of the model that may need recalibrating. There is also still need to improve model estimation of ET.

7.3 Conclusions

Despite the potential of grain legumes to improve nutrition and soil fertility they remain underutilised. There is need for more research on grain legumes to improve their value chain and make them more attractive. This should include underutilised grain legumes for crop and dietary diversity. The study showed that major grain legumes were higher yielding than underutilised grain legumes hence the hypothesis of the study was rejected. Any promotion of underutilised grain legumes should consider crop improvement of the crops. Grain legumes are suitable for production in water scarce areas. With the growing emphasis on improving WP, results of this study showed that this can be achieved under deficit irrigation and rainfed conditions. Under different environments, however, groundnut, dry bean and bambara groundnut showed much grain yield variability. Cowpea was the lowest yielding crop but exhibited the highest stability across environments.

Dry bean was early maturing which led to low ET relative to the other crops. Dry bean also had a significantly higher harvest index compared to the other crops. For groundnut, although it was late maturing and used more water, this often translated to high biomass and yield. For bambara groundnut, despite low stomatal conductance, ET was high. This was because of poor canopy development that led to significant unproductive ET through soil evaporation. Bambara groundnut was also late maturing, but this did not translate to high biomass and yield unlike for groundnut. Groundnut emerged, flowered and podded earlier than bambara groundnut allowing it more time for yield formation. Bambara groundnut was slow to flower and pod and this was reflected in the low harvest index.

The study showed that grain legumes had the potential to supply 40 – 60% of protein RDA. This confirmed the role of legumes as a source of dietary protein among poor rural people who may not be able to afford meat and dairy products. Dry bean and cowpea have potential to supply 40 to 60% of Fe and Zn RDA. The instability of grain yield also had negative implications on NWP. Nutritional water productivity proved to be a useful metric for linking food production to nutritional outcomes under water scarcity. AquaCrop was a suitable model for simulating growth, yield and ET of groundnut and dry bean. AquaCrop tended to overestimate ET, and the reason could not be established. Although the model showed potential to simulate growth, yield and ET, model testing in this study was limited due to monkey attacks in the field hence results were inconclusive. There is still need for further testing especially under different water regimes, soils and climate.

7.4 Recommendations and Future Directions

Based on the observations made in this study, the following technical and research recommendations are given;

i. Proper field assessments should be undertaken before studies are undertaken for any risk associated with wild animals and soils as this may affect study outcomes.
ii. Bambara groundnut should undergo crop improvement to improve the crop’s yield and reduce unproductive ET for it to be accepted as an alternative grain legume by farmers in the semi- and arid regions.

iii. The grain legumes under study showed static instability across environments. Any recommendations on production of grain legumes should assess the suitability of grain legumes for different environments. This requires studies and understanding on species × environment interaction of grain legumes.

iv. Breeding efforts for grain legumes should also not focus on improving yield but also improving adaptation to different environments and resilience to extreme weather events.

v. Late maturing varieties of grain legumes should be planted early (November) as late planting (January) resulted in poor yield. There should be studies to identify the best varieties for different cropping systems (intercropping, double cropping, crop rotation etc.).

vi. There is need for further studies benchmarking other underutilised grain legumes such as marama bean (*Tylosema esculentum*), lablab (*Lablab purpureus*), African yam bean: (*Sphenostylis Stenocarpa*) and velvet bean (*Mucuna pruriens*) to major grain legumes under the same environments.

vii. Future studies should explore effects of factors such as management practices (fertiliser levels and plant density), climate and edaphic factors on nutrient content and NWP for a range of legumes.

viii. AquaCrop has not yet been calibrated and tested for cowpea as a potential underutilised crop in water limited regions. Future studies should seek to address this gap.

ix. In this study testing of the AquaCrop model for groundnut and dry bean was limited by animal attacks. There is need for studies to further test the model under different under different environments and water management strategies.

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