Pre-breeding of architectural traits related to direct harvesting in dry bean.

By

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Declaration

I Mwiinga Mulube, declare that, this thesis is a reflection of my own work, except otherwise where indicated and it has not been previously submitted to any University for degree purposes. All consultations made on published work has been rephrased and clearly referenced and no copy and paste information from the internet has been included.

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As supervisors at the University of KwaZulu-Natal, we hereby approve this thesis for examination.

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Abstract

Dry bean (*Phaseolus Vulgaris L.*) is an important crop for direct human consumption worldwide. In South Africa, it is a major source of plant proteins and income among growers. The crop is mainly grown by commercial producers for the market in Mpumalanga, Gauteng, Northwest, Free State, Limpopo, KwaZulu-Natal and the Eastern Cape provinces. Dry bean is known to be one of the most labour intensive field crops, especially the harvesting operation. In order to maximise profits, commercial producers prefer using the direct harvesting system that has the advantages of labour efficiency and saving time, compared to the pull/cut and window followed by threshing harvesting system. However, the success of the direct harvesting system requires a cultivar with a suitable upright architecture. The upright bean architecture suitable for direct harvesting is a complex trait that may only be improved through indirect selection for sub-component morphological traits associated with the trait. It is therefore important to evaluate diverse genotypes for morphological traits associated with the upright bean architecture to improve the trait. This study was aimed at (1) evaluating architectural traits related to direct harvesting and establishing relationships amongst traits on selected genotypes from the Andean gene pool, (2) estimating the phenotypic and genotypic variation, heritability, and genetic gain of traits related to direct harvesting on selected genotypes from the Andean gene pool, and (3) evaluating the architectural traits related to direct harvesting and establish the relationships amongst traits in local South African genotypes.

The evaluation of architectural traits related to direct harvesting and establishing relationships amongst traits, was carried out on 30 Type I genotypes from the Andean gene pool. The trial was evaluated under field conditions in a 10 × 3 alpha lattice design at two sites. The traits collected were the days to physiological maturity, upright plant score, lodging, stem diameter, plant height, shattering, number of branches per plant, number of pods per plant, seed weight and seed yield. The analysis of variance showed highly significant differences ($p \leq 0.001$) on genotypes across all traits, except for the number of branches, which was moderately significant ($p \leq 0.05$). Superior genotypes were identified in each trait based on the grand mean. The stem diameter was identified to be important for multiple selections, because of its correlations with the upright plant architecture score, lodging, the days to physiological maturity and seed yield. Three principal components were extracted, accounting for 78.55% of total variation. Selection for the seed yield, stem diameter and plant height would be essential for improving the suitability to direct harvesting. The genotypes ADP 35, ADP 166, ADP 211, ADP 36, ADP 395, ADP 436, ADP 455, ADP 458, ADP 661, Mbomvu and Ukulinga were found to have thicker stem diameters and non-shattering, and therefore, they may be useful in improving both seed yield and the upright architecture suitable for direct harvesting.

The estimation of the phenotypic and genotypic variation, heritability and genetic gain of traits related to direct harvesting was also carried out on 30 Type I genotypes from the Andean gene pool. The trial was evaluated in a 10 × 3 alpha lattice design at two sites. The traits collected were the days to physiological maturity, upright plant score, lodging, stem diameter, plant height, shattering, number of branches per plant, number of pods per plant, seed weight and seed yield. The analysis of variance showed highly significant differences among genotypes on all traits except the number of branches per plant, which showed moderately significant differences. The highly significant differences indicate the presence of genetic variability in the data set. A significant interaction of genotype with the site was observed on days to physiological maturity, lodging, plant height and seed weight. The phenotypic coefficient of variation was slightly higher than the genotypic coefficient of variation for all traits, showing little environmental influence on the expression of traits. Generally, a high variability was observed in the population. Broad sense heritability estimates ranged from moderate to high, except for the number of branches per plant, which recorded a low heritability value of 29%. The moderate to high heritability and expected genetic gains observed in the population could be exploited through selection and hybridisation during the improvement of the upright bean architecture suitable for direct harvesting.

The evaluation of architectural traits related to direct harvesting, and establishing relationships amongst traits on local South African genotypes, was carried out on twenty four genotypes. The trial was laid out in a 6×4 alpha lattice design at Ukulinga Research Farm. The traits collected were, the days to 50% flowering, days to physiological maturity, upright plant score, lodging, stem diameter, plant height, shattering, number of branches per plant, number of pods per plant, seed weight and seed yield. The analysis of variance showed highly significant differences for the number of days to physiological maturity, days to 50% flowering, lodging, number of branches per plant, plant height, number of pods per plant, seed weight and the upright plant score, while it was very significant for the first pod insertion height and moderate for stem diameter, shattering and seed yield. Superior genotypes were identified using the grand means of the different traits and these genotypes may be used in a breeding programme to improve the suitability to combine harvesting. The correlation analysis showed that plant height would be useful in selection. However, an optimum height, to reduce lodging and improve the upright architecture should be selected for. The factor analysis revealed that seed yield, upright plant score, first pod insertion height, plant height and lodging had more influence on the variation in the data set and as such may be considered during selection. The cluster analysis grouped genotypes in two groups, while two genotypes were stand alone and the four principal components accounted for 78.55% of variation.

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Dedication

This thesis is dedicated to my dad Lazarus Mulube, my wife Collus and my daughter Chileleko for always encouraging me and giving me the reason to work hard.

Table of Contents

List of Figures

List of Tables

Abbreviations

CIAT	Centre for International Tropical Agriculture
ARC-GCI	Agricultural Research Council-Grain Crop Institute
AGRA	Alliance for a Green Revolution in Africa
RAPD	Random Amplified Polymorphism
ISSR	Inter-Simple Sequence Repeat
AFLP	Amplified Fragment Length Polymorphism
DNA	Deoxyribonucleic acid
RFLP	Restrictive Fragment Length Polymorphism
GCA	General combining ability
SCA	Specific combining ability
H^2	Broad sense heritability
h^2	Narrow sense heritability
σ_p^2	Phenotypic variance
σ_g^2	Genotypic variance
σ_e^2	Error variance

σ_a^2	Additive variance
σ_d^2	Dominance variance
σ_{gs}^2	Genotype by site variance
UPS	Upright plant score
SD	Stem diameter
FPIH	First pod insertion height
LDG	Lodging
SHT	Shattering
NB	Number of branches per plant
DPM	Days to physiological maturity
PPP	Number of pods per plant
SW	Seed weight
Y	Seed yield
ADP	Andean Diversity Panel
masl	Meters above sea level
PH	Plant height

F50%	Days to 50% flowering
ANOVA	Analysis of variance
DF	Degrees of freedom
cm	Centimetres
mm	Millimetres
ha	Hectare
r	Correlation coefficient
PCA	Principal component analysis
PC	Principal component
PVC	Phenotypic coefficient of variation
GVC	Genotypic coefficient of variation
GA	Genetic advance
GG	Genetic gain
MS	Mean sum of squares
MS_g	Mean sum of squares for genotype
MS_s	Mean sum of squares for site

MS_{gs}	Mean sum of squares for genotype by site
MS_{e}	Mean sum of squares for error
EMS	Expected Mean Squares
g	Degrees of freedom for genotype
r	Degrees of freedom for replications
gs	Degrees of freedom for genotype by site
s	Degrees of freedom for site
CV	Coefficient of variation
FAO	Food and Agriculture Organization
EABRN	East African Bean Research Network
DAFF	Department of Agriculture, Forestry and Fisheries
LSD	Least Significant Differences

Chapter 1

Thesis introduction

1.1 Introduction

Dry bean (*Phaseolus vulgaris* L.), is one of the most important legumes in the world (CIAT, 2005) and is grown on an area of approximately 27.4 million hectares globally, with a production of 21.7 million tons and an average yield of 0.78 t ha^{-1} (Nedumaran et al., 2015). After soybean, dry bean is the most widely grown legume in Sub-Saharan Africa and is cultivated on approximately 5.8 million hectares with the total production of 3.8 million tons (average yield of 0.65 t ha^{-1}) (Nedumaran et al., 2015). However, the average yield is very low compared to an average yield of 1.8 t ha^{-1} obtained in the developed world (Nedumaran et al., 2015). This is attributed to abiotic and biotic stresses coupled with poor crop management systems (Singh, 2001). Sub-Saharan Africa smallholder farmers, normally grow the crop on less than a hectare, except for South Africa and Sudan where growers plant larger areas (Muthoni et al., 2013). Dry bean is an important crop in South Africa where it is grown for both food and trading (Department of Agriculture, 2011). It is a major source of proteins across different income levels both in the rural and urban areas, its tender leaves and immature pods can be cooked and consumed as a vegetable, while mature seeds are consumed as whole grain (Atilla et al., 2010). Dry seeds are a good source of essential minerals, soluble fibres and phytochemicals. Apart from providing an income to growers through trade, dry bean is also used in rotations with cereals because of its intrinsic role in fixing atmospheric nitrogen (CIAT, 2004),

South Africa produces approximately 75% of the dry bean consumed in the country, while about 25% is furnished by imports (Department of Agriculture, 2011). The crop is mainly grown in Mpumalanga, Gauteng, Northwest, Free State, Limpopo, KwaZulu-Natal and the Eastern Cape provinces. The varieties grown are the determinate or bush (Type I) and the indeterminate compact upright (Type II). In terms of size and seed colour, the small white beans, mainly used for canning, account for about 10 to 20% of local production, the red speckled or speckled sugar bean contribute approximately 65 to 75% of local production, while the large white kidney bean accounts for 5 to 10%, and finally carioca and alubia beans combined account for 1 to 5% of local production (Department of Agriculture, 2011). Generally, there has been an improvement in average yields attributed to efforts in breeding, from 0.6 t ha^{-1} obtained in late seventies to 1.0 – 1.2 t ha^{-1} being obtained currently. Despite the tremendous improvement in yield per unit area, South Africa still experiences a deficit in dry bean. This shows the need for exploring more ways of improving production and productivity of the crop, like labour efficiency, to facilitate acreage expansion.

Dry bean commercial prices are known to be high compared to other legumes such as soybean and groundnuts. However, dry bean has a reputation of being one of the most labour intensive field crops to harvest (Joubert, 2011). This reputation has restricted bean farmers from expanding their production areas. Direct harvesting of dry bean has challenges because of the plants' tendency to lodge, shatter and carry the pods close to the ground. The direct harvesting system of dry bean requires a cultivar with specific attributes, such as an upright strong-stem to prevent the plant from lodging, a height of about 50 cm, pods raised at least 5 cm from the ground and resistant to shattering to avoid spillage (Acquaah et al., 1991). Joubert (2011), stressed that the direct harvesting system is the future for bean production, because it reduces harvesting costs tremendously if done well. In South Africa, hiring a combine harvester cost farmer's an average of R600 hr^{-1} and can harvest a block of 7 ha in two hours in one operation (Joubert, 2011). With the labour efficiency of direct harvesting beans, farmers are provided with an opportunity to expand their production areas (acreages). Other than labour efficiency, the upright cultivar suitable for direct harvesting comes with additional advantages that include a reduction or avoidance of fungal diseases such as white mold (*Sclerotinia sclerotiorum*) and a good quality of the beans even in wet season, because pods do not touch the ground.

1.2 Problem statement and justification

Dry bean production cost in South Africa is increasing due to high cost of labour. Direct harvesting will contribute to greater profitability of the crop. Therefore, there is need to evaluate and breed cultivars for suitability in direct harvesting.

1.3 Main objective

- To develop a breeding strategy for the development of upright dry bean cultivars suitable for direct harvesting.

1.3.1 Specific objectives

- To evaluate architectural traits related to direct harvesting and establish trait relationships on selected genotypes from the Andean gene pool.
- To estimate the phenotypic and genotypic variance, heritability, and genetic gain of traits related to direct harvesting on selected genotypes from the Andean gene pool.
- To evaluate architectural traits related to direct harvesting and establish trait relationships on South African genotypes.

1.4 Thesis outline

Chapter 1	Thesis introduction.
Chapter 2	Literature review.
Chapter 3	Evaluation of architectural traits related to direct harvesting for selected genotypes from the Andean gene pool.
Chapter 4	Estimation of the phenotypic and genotypic variation, heritability, and genetic gain of traits related to direct harvesting in dry bean.
Chapter 5	Evaluation of architectural traits related to direct harvesting for South African genotypes.
Chapter 6	Overview of the study.

1.5 References

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Chapter 2

Literature review

2.1 Introduction

Unlike *Glycine max L.*, little mechanized harvesting of dry bean (*Phaseolus vulgaris L.*) is done in South Africa, despite the crop being one of the most labor intensive to harvest manually (Johnson et al., 1955). Recently, there has been an increased interest from South African growers in direct harvesting as a way to avoid the high cost of labor associated with manual harvesting (Joubert, 2011). In addition, the cultivar suitable for direct harvesting can improve the quality of the crop, by avoiding fungal diseases such as *Sclerotinia sclerotiorum*. Despite the recent interest, there are few cultivars that are suitable for direct harvesting, hence the need for a breeding intervention to develop such a cultivar. This chapter will therefore review important literature that would aid in developing an efficient breeding strategy for dry bean cultivars that can be used for direct harvesting. It will first seek to understand dry bean growth habits and their implication in relation to direct harvesting, followed by the diversity of dry bean in terms of gene pools. It will then outline a detailed study of cropping systems in dry bean. The chapter will further look at the ideotype breeding in brief and the trends that has taken place in dry bean, the harvesting methods and the architectural requirements for a suitable cultivar for direct harvesting. Heritability will be reviewed in brief, followed by its importance in plant breeding. Finally, the chapter will review literature on heritability of traits associated with upright plant architecture in dry bean.

2.2 Dry bean growth habits

The growth habit of dry bean germplasm are classified as determinate or indeterminate (Mohamed et al., 2007). Plants with a determinate growth habit stop stem elongation the moment terminal flower racemes develop on the main stem or lateral branches. Plants with an indeterminate growth habit continue with flowering and pod filling along with stem elongation, provided there are favorable conditions for plant growth such as high temperature and adequate moisture. In addition to the determinate/indeterminate classification, Singh (1982) proposed a classification that separates bean germplasm based on further morphological growth characteristics. It classifies bean germplasm into four distinct growth habits namely; Type I, II, III and IV. Type I is a determinate growth habit that is referred to as the determinate bush bean. It stops growing once flowering starts. The Type I habit has a lot of branches where pods set, which gives it an advantage of keeping pods off the ground at maturity. Generally, the plant is short and characterized with early and uniform maturity. Type II is an indeterminate growth habit that is referred to as the upright short vine. This habit has a narrow profile with a few branches usually three to four maintained at acute angles to the main stem. Unlike in Type I, pods of the Type II growth habit are set from the third node upwards to the seventh or eighth node. The pods are concentrated in the middle of the plant. This growth habit has the capacity to remain upright even after pod filling and pods do not touch the ground. Plants with a Type II growth habit generally take longer to mature than those with a Type I. Type III is an indeterminate growth habit that is referred to as the vine type. It has a prostrate growth habit with disorganized branching. This growth habit exhibits an upright stature, but lacks strength to remain upright during pod filling. It shows a tendency to climb if support is provided. Pod set is normally concentrated at lower nodes of the plant near the ground. Most of the pods of this habit have a curved shape because they tend to bend when they touch the ground. Type IV is an indeterminate habit that has a very strong tendency to climb. It is therefore referred to as pole bean because its production requires a trellis system. This growth habit contains a lot of nodes and long internodes (Kelly, 2001).

2.3 Wild and cultivated gene pools of *Phaseolus vulgaris*

There are two major gene pools in the cultivated *P. vulgaris*, namely the Andean and Middle American gene pools (Asfaw et al., 2009). These gene pools resulted from evolution under natural conditions before domestication followed by farmers selection during cultivation (Gepts, 1998). Cultivated dry bean originated from South America, while its wild ancestor is believed to have originated in southern Ecuador and northern Peru (Kelly, 2010). From here it spread throughout northwestern Argentina and northern Mexico, and wild beans can be traced in this geographical range today (Asfaw et al., 2009). The classification of beans according to origin based on DNA analysis has shown that wild beans were domesticated independently in all its geographical range from Argentina to Mexico (Kelly, 2010). The wild beans domesticated in Middle-America, i.e. from Colombia northwards, belong to the Middle American gene pool, while those domesticated in the Andean regions from southern Ecuador belong to the Andean gene pool (Van Schoonhoven and Voysest, 1991). Apart from the two major gene pools, Debouck et al. (1993), postulated another wild population of *P. vulgaris* that is distinct from the two gene pools and is considered the third gene pool of *P. vulgaris*. The separation of *P. vulgaris* into gene pools is based on extensive studies on archeology, morphology, bio- chemistry and the molecular characteristics of the crop and has been confirmed through isozyme markers (Koenig and Gepts, 1989, Santalla et al., 2004), molecular markers of RFLP (Chacon et al., 2005), electrophoretic profile of the phaseolin storage protein (Gepts et al., 1986, Perreira and Souza, 1992, Solano, 2005), AFLP (Maciel et al., 2003), morphological markers (Chacon et al., 2005, De La Cruz et al., 2005), RAPD (Beebe et al., 2000) and ISSR (De La Cruz et al., 2005).

The two major gene pools are further subdivided into races based on agro-ecological adaptation (Kelly, 2010). Gepts (1998), defined a race as a biological unit with some genetic integrity and a distinct cohesion of morphology, geographic distribution, ecological adaptation, and frequency of breeding behavior. Members of a specific race originated in some geographical region at some time in the history of the crop. Morphological, physiological, cytogenetic, genetic traits, as well as isozymes and seed proteins, have been used to characterize crop races. The Andean gene pool has three races namely, Nueva Granada, Peru and Chile, while the Middle American gene pool also has three races and these are Mesoamerican, Durango and Jalisco and a fourth race unique only to Guatemala (Gepts, 1998).

The Nueva Granada race comprises three growth habits; Types I, II and III. Seed sizes vary from medium (25-40 g 100 seeds^{-1}) to large, with kidney or cylindrical shapes that greatly vary in color. Members of this race have intermediate to long internodes, their pods break at placental and ventral sutures. This race is dominated by a T type phaseolin pattern and an mdh-1^{100} allozyme allele. Members of this race are early maturing, not sensitive to photo-period, harbor resistance genes to common mosaic virus, halo blight, anthracnose and angular leaf spot. Examples of germplasm from this race includes large seeded kidney bean, bush cranberry and most snap beans (Kelly, 2010).

The Chile race is dominated by the Type III growth habit. It has small to medium seed sizes which are round to oval in shape and the plants short internodes. Its characteristic allozyme allele is Mdh-1^{100} and is dominated by a C and H phaseolin pattern. Race Chile is widely distributed in regions of lower altitudes such as southern Peru, Bolivia, Chile and Argentina. The examples of member of this race includes the vine cranberry beans and different types unique to Chile (Kelly, 2010).

The Peru race is dominated by germplasm of indeterminate or determinate Type IV growth habit (Debouck et al., 1988) and characterized by large seeds that are round or oval in shape though sometimes elongated, large hastate basal leaves, ovate and large leaflets, long (10-20 cm) and leathery pods that breaks originating from the placental sutures and long and weak internodes. This race is dominated by C, H and T type phaseolin patterns as well as an Mdh-I^{103} allozyme allele. Members of this race are highly sensitive to photo period, are early maturing and are distributed (>2000m altitudes) from the Northern Colombian highlands to Argentina. The examples includes overitos, nunas, triachos and yellow beans.

The Mesoamerica race, like the Nueva Granada race, has all the four growth habits of dry bean namely; Type I, II, III and IV. It has pods of 8 to 15 cm long that are slender, fibrous and easy to thresh. Its seeds are small i.e. 25 g 100 seed^{-1} and are of different colors. The Mesoamerican race has small to intermediate leaves and internode lengths. The dominant phaseolin type for this race is S, though sb and B are also present. Some germplasm of this race carry the DI-1 gene, which result in F1 hybrid lethality in the presence of DI-2 gene of the Andean origin (Gepts and Bliss, 1985). The Mesoamerican race is distributed throughout the tropical low and intermediate altitudes of Mexico, Central America, Colombia, Venezuela and Brazil. This race is a source of genes for resistance to bean common mosaic virus (II genes), tolerance to angular leaf spot and bean golden mosaic virus, insensitivity to photoperiod, and tolerance to high temperatures, moisture stress and low soil fertility. The examples of cultivars from this race includes the small seeded navy and the black beans (Kelly, 2010).

The Durango race is dominated by the Type III growth habit which has small to medium ovate leaves, thin stems and branches and short internodes. Fruiting normally starts from the bottom and is concentrated at basal nodes. Germplasm of Durango has medium sized flat pods that are 5-8 cm long, with medium seed sizes of 25-40 g 100 seed^{-1}. A whole range of seed colors are found in this race such as tan, yellow, cream, gray, black, white, red and pink. It is dominated by the S type of phaseolin pattern, though sd type is also present. Durango race has a characteristic alloenzyme allele Me^{102} (Singh et al., 1991). This race is widely found in semi-arid central and northern highlands of Mexico. The Durango race is a source of early maturity, drought tolerance, high harvest index and positive general combining ability (GCA) for seed yield. It also harbors genes for tolerance to viral diseases and anthracnose. The phaseolin allozyme allele present in this race is DI-1 (Singh et al., 1991).

The Jalisco race is dominated by indeterminate growth habit Type IV. Its plant height can go up to 3 m in its natural habitat. Germplasm of this race have long internodes and as a result it has weak stems and branches. It has ovate, hastate and relatively large trifoliate terminal leaflets. The Jalisco race has pods that are 8-15 cm long, with five to eight medium sized seeds that are round, oval or slightly elongated and kidney shaped. This race is dominated by the S type phaseolin pattern and the Me^{100} allozyme allele. Jalisco is characterized by high seed yield, positive GCA for yield, resistance to anthracnose, tolerance to low soil fertility and angular leaf spot. Examples of cultivars from this race includes small red and pink beans (Kelly, 2010).

2.4 Dry bean cropping systems

Dry bean is grown under a range of conditions. In the recent past, the crop was predominantly a small- holder crop in Africa, but with the introduction of mechanization, a lot of emergent and commercial farmers have ventured into bean production. Bean production systems ranges from the highly mechanised, irrigated and intensive production of Type I and II beans to multiple cropping systems of Types II, III, and IV with cereals and other crops such as bananas, sugar-cane and coffee. Multiple cropping systems are normally used by small holder farmers with limited or no purchased technical inputs. Such systems are associated with low yields. Akibode and Marendia (2011) reported yields of 0.5 t ha^{-1} under small holder production in Kenya and Tanzania. The cropping system used in dry bean production, the agronomic and biological factors, and the germplasm of the crop have a great effect on the yield of dry bean (Graham and Ranalli, 1997). The type of cropping system selected in a particular area is highly dependent on rainfall pattern, temperature, environment conditions, economics of production and the optimal planting densities for different growth habits required. Wooley et al. (1991), outlined five major cropping systems for dry bean production. These are sole cropping, relay cropping, row intercropping, mixed cropping and intercropping with other cereals.

In sole cropping system, Type I, II and III are grown as a sole crop (Graham and Ranalli, 1997). In relay cropping, where dry bean is often planted with maize or other cereals, the dry beans are planted when cereal crop reaches its physiological maturity. Under this system, all the four growth habits can be used, and in the case of Type IV, the cereal plant serves as support for climbing beans. The row intercropping system is where dry bean is intercropped with other cereals, usually maize. Only Types I and II are grown under this system. The other cropping system used in dry bean production is mixed cropping, where the dry beans are grown with a range of different crops intermingled together. All the four growth habits are used under this system. In the developed world, such as Europe and North America, dry bean production is highly mechanized. The crop is mono-cropped on flat land with mechanization (a variant to traditional sole cropping). This system uses a lot of purchased inputs such as fertilizers, pesticides, fuel and irrigation. High yields are normally reported under this system ranging from 1-3 t ha^{-1}. Under this mechanized mono-cropping system, only Types I and II growth habits are preferred because of their suitability for combine harvesting (Graham and Ranalli, 1997).

2.5 The concept of ideotype breeding

The early plant breeding programs were focusing on defect elimination and selecting for high yield, while the ideotype breeding concept introduced by Donald (1968), allow breeders to manipulate subcomponent plant traits in order to improve a complex trait such as yield or any other complex trait of economic importance like developing a cultivar suitable to a specific production system. A plant ideotype is one with model characteristics that have a positive impact on photosynthesis, growth, grain production and is adapted to a specific production system (Donald, 1968). Vandenberg and Nleya (1999), stated that, the choice of the specific trait to be modified, is dependent on environmental conditions and the production system targeted for the crop. Environmental conditionals can for example refer to rain fed or irrigated conditions, whereas production systems can refer to a manual or mechanised production systems. Ideotype breeding became important for most of the major field crops with the introduction of large scale mechanised farming systems in the early 2000s (Vandenberg and Nleya, 1999). Some of the crops with success in ideotype breeding for mechanization include wheat (*Triticum aestivum L.*), rice (*Oryza sativa L*.), sorghum (*Sorghum bicolor L*) and maize (*Zea mays L.*). Donald (1968) also stated that, an ideotype plant is highly efficient because it makes a low demand of resources per unit of dry matter produced.

2.6 Breeding plant ideotype

Plant breeders normally develop a plant type which they feel would be superior in yield or any other desirable trait. Plant ideotype selection outlined by Donald (1968), is a systematic and scientific concept of developing desired plant types using morphological parameters. The concept involves defining an ideal plant that would perform well under field conditions. For instance, in cereal crops, not all tillers produced in the early growth stages develop into culm bearing ear heads and grains resulting in waste of resources (Tandon and Jain, 2004). Therefore, a plant type that is theoretically efficient should be defined based on the knowledge of plant physiology and morphology. After defining such a plant type, breeders could go on and select the plant type rather than yield. For instance, the proposed ideotype for high grain yield in wheat is a uniculm plant with few small erect leaves, relatively shorter height, short stem, awned large erect earhead with many florents' and high proportion of seminal roots. The initial emphasis of ideotype breeding was on morphological traits. However, it has been extended to include physiological, biochemical, anatomical and phenological traits (Rasmusson, 1987). Before any character is included as a parameter in developing a plant type, its contribution to yield should be assessed and known (Kelly et al, 1998). Some characters are easy to measure while others are difficult. However, studies have been carried out in a range of crops to identify effective characters in developing plant types for high yield or any other desired trait. The concept of plant type selection has a potential of accelerating the adaptation of crops to a production system or yield gains.

2.7 Trends in architectural or ideotype breeding in dry bean

The reported success of ideotype breeding in dry bean is the conversion of Type III growth habit to Type II (Kelly and Adams, 1987). Despite possessing a high inherent yield potential, a Type III habit is prostate and lacks stem strength to remain upright, it lodges with branches on the ground, hence exposing the pods to sclerotinia. It's for these reasons that a Type III *habit* is not suitable for mechanized harvesting (Soltani et al., 2016). Down and Anderson (1956), reported the development of a Type I cultivar small white canning bean from Type III using X-ray mutation that was named Sanilac. Sanilac is a determinate bush navy bean cultivar that has prolific branching and pod set on branches with a good clearance from the ground. Sanilac addressed the disease and seed quality problems in dry bean, but highly compromised the yield potential. Breeders later used a Type II black bean as a source of alleles for an upright dominant stem, little branching, a narrow profile and a good pod clearance from the ground, to develop the cultivar C-20 (Kelly et al., 1984). Cultivar C-20 became the foundation of the Type II small white canning bean cultivars widely grown today. The yield potential of the developed Type II cultivars was later improved beyond the original Type III cultivars (Singh et al., 2007). Another report by Kelly et al. (1992), shows the development of a cultivar Type II cultivar alphine using a multi-step recurrent selection. Cultivar alphine is characterized by a tall, more upright and narrow profile. It also has a good pod clearance height from the ground, 2-3 basal branches at acute angles and a thick hypocotyl that gives it a stronger stem. The development of such upright cultivars, resulted in the increased adoption of direct harvesting methods in dry bean in the developed world, which is now spreading to the developing world, which has been lagging in terms of mechanization, mainly because of lack of a suitable cultivar specifically for direct harvesting. The lack of improved cultivars in general, and factors such us diseases, pests and low inputs, has resulted in low productivity of beans in southern Africa. Kelly (2013), Ministry of Agriculture & Livestock (2011) and Akibode and Marendia (2011) reported average yields of 0.5 t ha^{-1} in Zambia, Malawi and Tanzania. Direct harvesting has gained popularity, because growers understand that the minor yield loss due to mechanised operation will be compensated by the time and cost saving, since only one operation is done compared to two or three operations under the conventional cut and pull harvesting method (Smith, 2004). Losses are further reduced with the use of the right cultivars with high pod set and with reduced shattering (Eckert et al., 2011).

2.8 Dry bean harvesting methods and suitable plant architecture for direct harvesting

Direct harvesting system is where dry bean is directly harvested at maturity, threshed and winnowed in one operation, using a combine harvester, after which the beans are transported in bulk to local elevators where the crop is cleaned, stored, graded and shipped to the market (Nowatzki, 2013). The other harvesting systems used in dry beans are the manual or mechanical cut and pull, whereby the beans are placed in a windrow. When the beans are dry enough they will be mechanically threshed. In a small-holders farming system, the plants are beaten with sticks to remove the beans. In direct harvesting system, a wider crop area is harvested in a short period of time thereby giving it an advantage of saving time and labor compared to the manual or mechanical cut and pull method. In contrast to the manual harvesting method which is used across beans growth habits, a direct harvesting method requires a suitable cultivar that combines upright plant architecture and competitive yields. The need for a cultivar suitable for direct harvesting has increased in South Africa, with the recent shift in bean production, from the traditional small scale, to the highly mechanised commercial production systems. Acquaah et al. (1991), postulated a suitable bean cultivar for direct harvesting as one with an upright architecture, strong hypocotyl, shattering resistant, shot internodes and with branches at acute angles. Acquaah et al. (1991), description of a suitable cultivar for direct harvesting is the Type II growth habit, However some of the available upright short vine cultivars lack in some other important traits needed for direct combining such as high yield, resistance to lodging, tolerance to common diseases and shattering resistance. The suitability for direct harvesting is a complex trait. It is therefore important to understand the interrelationships of its components in order to successfully breed for it (Acquaah et al., 1991). Adams (1982), bred for an upright bean type for direct harvesting in the humid Midwest (USA). He described it as an architype because it was a product of specific morphological architectural features of the plant. He found that a suitable plant type should have three to five upright basal branches, a thick hypocotyl, narrow plant profile, be high yielding in keeping with a commercial class requirement, and with a plant height between 50 and 55 cm, with main-stem nodes numbering 12 to 15, upper internodes longer and more numerous than basal ones, a leaf area index of 4 at flowering and Type II growth habit. Similar to Adam’s description of a suitable plant type for direct harvesting, (Janick, 1992), stated that in order to improve the upright characteristic required for direct harvesting, there is need to modify plant height, internode length, number and thickness of branches, branching pattern and root morphology. Acquaah et al. (1991), also stated that breeding programs focusing on suitable cultivars for direct harvesting should emphasize selection on hypocotyl diameter, plant height, branch angle and number of pods. Some of these morphological traits are highly heritable, therefore they can easily be manipulated in breeding programs. However the complementarity of these contributing morphological traits are not properly understood (Janick, 1992) .Apart from being suitable for direct harvesting, the upright plant has other advantages such as reduction of fungal diseases such as *Sclerotinia sclerotiorum* (because pods do not touch the ground) and reducing losses due to lodging, especially under prolonged rainfall (Silva et al., 2013)

2.9 Heritability

Heritability is an important genetic component in determining the effectiveness of selection in a crop breeding program such as for dry bean (Munganyika et al., 2015). It provides the degree of resemblance between relatives and hence plays a vital role in developing breeding strategies for plant improvement (Mukamuhirwa et al., 2015). Heritability is defined as the total phenotypic variance of a population that is attributed to the effects of genes and is denoted by a symbol H^2 (Kearsey and Pooni, 1996). Two forms of heritability exists, namely broad sense heritability denoted by H^2 and narrow sense heritability denoted by h^2. Broad sense heritability is the ratio of the total genetic variation to the total phenotypic variation. The observed variation in a group of individuals σ_p^2, is due to the genetic variation σ_g^2 and the environmental variation σ_e^2. Phenotypic variation $(\sigma_p^2) = \sigma_g^2 + \sigma_e^2$. The genetic variation is the heritable component, while the environmental component is non-heritable. Broad sense heritability is therefore estimated as $H^2 = \frac{\sigma_g^2}{(\sigma_g^2 + \sigma_e^2)}$. Heritability in the broad sense is a reflection of all possible genetic contributions to the observed variance of the population such as dominance, epistasis, maternal effects, and paternal effects. If all these genetic components are available, broad sense heritability is estimated as $H^2 = \frac{\sigma_a^2 + \sigma_d^2}{\sigma_a^2 + \sigma_d^2 + \sigma_e^2}$.

The genetic variation $(\sigma_g^2)$is composed of three portions, which are additive genetic variation (σ_a^2) (the portion of genetic variation that can be accounted for by the linear regression of genotypic value on the gene content), the dominance variation (σ_d^2) (caused by dominance deviations from the additive scheme) and the epistatic variation (σ_i^2) (due to interaction among non-allelic genes). The ratio of the additive genetic variation to the total phenotypic variation gives heritability in the narrow sense estimated as $h^2 = \frac{\sigma_a^2}{(\sigma_a^2 + \sigma_d^2 + \sigma_e^2)}$. Narrow sense heritability is very important in plant breeding because it provides the breeding value of the population. It measures the portion of variation which is due to the additive effect of genes in a population. Heritability values range from 0 to 1, i.e. $0 \le h^2 \le H^2 \le 1$. The concept of heritability in the broad sense is useful when determining the relative influence of genotype and environment on the phenotypic differences. Usually the plant breeder is more interested in the narrow sense heritability because it is the chief cause of resemblance between relatives through the additive genetic variance. So unless it is specified, the word heritability means heritability in the narrow sense. When heritability for a certain trait is high, the trait is said to be highly heritable, whereas when it is low, it is said to be lowly heritable. Heritability is a property of both the character and the genetic structure of the population at a given environment (Tada, 2015).

2.10 The importance of heritability in plant breeding

Heritability provides a measure of genetic variation, that is, the variation upon which all the possibilities of changing the genetic composition of the population through selection depends on (Hollande et al., 2003). In other words, knowledge of its magnitude gives an idea on whether a trait of interest would benefit from breeding or not. If the narrow sense heritability of a trait is high, it simply means that the use of plant breeding methods would likely be successful in improving the trait (Acquaah, 2009). Knowledge of heritability helps in choosing the most effective selection method to employ in a breeding programme, whereby selection methods based on phenotype are effective when heritability is high. In other words, heritability gives a measure of the accuracy with which the selection for a genotype can be made from a phenotype of the individual or a group of individuals. Another important function of the heritability is its role in predicting the breeding value of an individual as well as in predicting the genetic improvement expected as a result of the adoption of particular scheme of selection. Thus the best estimate of an individual’s breeding value is the product of its phenotypic value and the heritability. The magnitude of heritability dictates the choice of selection method and breeding system. High heritability estimates indicate that additive gene action is more important for that trait, and selective breeding i.e. mating of the best to the best should produce more desirable progeny. Low estimates, on the other hand, indicate that non-additive gene action such as over-dominance, dominance, and epistasis are important (Tada, 2015).

2.11 Heritability of upright plant architecture in dry bean

Upright plant architecture is a complex trait that is determined by several morphological traits. Acquaah et al. (1991) outlined the stem diameter, plant height, branch angle and number of pods as the major morphological determinants of upright architecture. Silva et al. (2013) in his studies on the inheritance of upright plant architecture in dry bean, used an overall plant architectural score (Collicchio et al., 1997) and specific morphological traits that included the stem diameter, mean plant height and grain yield. He found that upright plant architecture and stem diameter were controlled by the additive genetic effect. He reported heritability estimates of 0.61 for upright architectural score and 0.81 for stem diameter and concluded that the latter can be used to select for the former, since it's highly heritable and easy to select. Teixeira et al. (1999) also carried out a study on genetic control of upright architecture in segregating populations of dry bean. He used ramification degree, internode length, internode diameter, height of insertion of first pod and the degree of uprightness. He found that upright plant architecture is controlled by additive genes, but highly influenced by the environment. A conclusion was therefore made that it's possible to successfully breed for upright architecture if selection is done for a few generations or under different environments.

2.12 Conclusion

Upright plant architecture is an important economic trait in dry bean production especially for emergent and commercial farmers who grow the crop for marketing. It makes it possible to directly combine dry bean, which gives an advantage of efficiency to the grower. In addition, it also makes it easy to carry out cultural practices such as weed control, irrigation, preventing fungal diseases such as sclerotinia, and improves grain quality. Above all, the possibility of direct harvesting enables farmers to avoid the high cost of labour associated with manual harvesting. Little breeding intervention has been done in improving the trait, therefore it is of great importance to evaluate genotypes from various sources for traits related to the upright architecture suitable for direct harvesting and also to estimate the phenotypic and genotypic variation, heritability, and genetic gain of traits related to direct harvesting. This research will assist in developing an efficient breeding strategy for the trait.

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Chapter 3

Evaluation of architectural traits related to direct harvesting for selected genotypes from the Andean gene pool.

Abstract

The upright bean architecture is a very important trait in the success of direct harvesting in dry beans. However, upright bean architecture is a complex trait that can only be improved by indirectly selecting for sub-component morphological traits that are associated with the upright bean architecture. This study was aimed at evaluating a set of genotypes from the Andean gene pool for upright bean architecture suitable for direct harvesting, using the upright plant grade (score) and morphological traits, as well as to determine functional correlations between morphological traits and the upright bean architecture. Thirty Type I genotypes of the Andean gene pool were planted at Potchefstroom and Ukulinga Research Farm in the 2016/17 growing season. The following traits were collected; upright plant score (UPS), stem diameter (SD), first pod insertion height (FPIH), lodging (LDG), shattering (SHT), number of branches per plant (NB), days to physiological maturity (DPM), number of pods per plant (PPP), seed weight (SW) and seed yield (Y). The analysis of variance, Pearson's correlations and principal component analysis were carried out. Significant differences ($p \leq 0.001$) were observed on genotypes across all traits, except for the number of branches, which was significant at $p \leq 0.05$. Superior genotypes were identified in each trait based on the grand mean. The stem diameter was identified to be important for simultaneous selection, because, selecting thicker stems would improve the upright plant architecture score, reduce lodging, increase the days to physiological maturity and also improve yield. Furthermore, the factor analysis revealed the importance of seed yield, stem diameter and plant height for consideration for selection when breeding for suitability to direct harvesting.

Keywords: Direct harvesting, dry beans, morphological traits, upright architecture.

3.1 Introduction

The harvesting procedure of dry bean is important to a producer in terms of risk and cost (Thomas et al., 2016). There are generally two methods of harvesting dry beans namely; firstly the manual or mechanical pulling of the plants and placing them into windrows followed by a threshing operation and secondly the direct combining system (Harrigan et al., 1992). Harvesting dry beans with the direct combining system, requires only a single pass of the combine at maturity (one operation), while the manual pulling and windrow system followed by threshing requires two operations (Jones, 1999). The direct combining system is associated with a problem of high header grain losses and difficulties in threshing immature pods (Thomas et al., 2016). However, the system is cheaper and saves time compared to the windrows followed by threshing system. The direct combining system requires a suitable cultivar to reduce losses. A suitable cultivar for direct harvesting is one that combines an upright plant architecture and a competitive yield with pods hanging at above 5 cm from the soil at harvesting (Nowatzki, 2013).

Upright plant architecture is a trait of economic importance in dry bean (Soltani et al., 2016). It has the advantage avoiding fungal diseases such as sclerotinia, assurance of grain quality and above all the possibility of direct harvesting (Teixeira et al., 1999), which is a cost effective harvesting method (Joubert, 2011). Upright plant architecture is a complex trait, which is a product of factors such as the growth habit, stem diameter, plant height, number and angle of branches, number and length of internodes and pod distribution (Oliveira et al., 2015). Therefore, the breeding approach for a direct harvesting cropping system follows the approach of ideotype breeding (Acquaah et al., 1991), and its success depends on the selection of sub-component traits other than the trait itself. As a whole, upright plant architecture is evaluated using the plant architecture grade scale (Collicchio et al., 1997). However, this method proves to be inefficient on its own, because it is visual, requires an experienced evaluator and is difficult to use with individual plants. To supplement the architectural grade scale method of evaluation, Acquaah et al. (1991), suggested an evaluation method that uses effective morphological indicators of upright plant architecture. They used a stepwise multiple regression method to determine which among a range of architectural traits had effective indications of upright plant architecture. They found that the stem diameter, plant height, branch angle and number of pods on the main stem were important factors in determining upright pant architecture. Though there has been no agreed set of morphological traits which have a substantial contribution to the upright architecture suitable for combine harvesting, a range of different morphological traits have been used by various researchers in evaluating upright plant architecture suitable for direct harvesting. Brothers and Kelly (1993), used branch angle, stem diameter and plant height to evaluate the trait. Moura et al. (2013), evaluated 36 dry bean lines using a range of architectural traits and observed that branch angle, plant height and stem diameter were highly related to upright plant architecture. Soltani et al. (2016), also evaluated bean lines of different growth habits for upright plant architecture using plant height, stem diameter, first pod insertion height, number of branches, days to flowering, days to maturity, shattering, lodging, pods per plant, seed weight and seed yield.

The objectives of this study were to evaluate architectural traits related to direct harvesting and establishing trait relationships on selected genotypes from the Andean gene pool. This study was important in identifying possible parents that could be used in future breeding programmes for upright bean cultivars suitable for direct harvesting.

3.2 Materials and methods

3.2.1 Plant materials

The study evaluated 30 Type I (determinate bush) genotypes from the Andean gene pool, of which, 25 genotypes were sourced from the Agriculture Research Council while five came from Pro-Seed, a seed company based in Pietermaritzburg. The genotypes were selected based on the leading market classes in South Africa (Department of Agriculture, 2011). The descriptions of the materials is presented in the Table 3.1.

Table 3.1 List of Type I dry bean genotypes evaluated and their seed colour classification.

Genotype	Seed colour
ADP 166	Red speckled
ADP 180	Red speckled
ADP 208	Red speckled
ADP 211	Red speckled
ADP 242	Red speckled
ADP 35	Red speckled
ADP 36	Red speckled
ADP 395	Red speckled
ADP 434	Red speckled
ADP 435	Red speckled
ADP 436	Red speckled

Genotype	Seed colour
ADP 437	Red speckled
ADP 455	Red speckled
ADP 458	Red speckled
ADP 470	Red speckled
ADP 515	Cranberry
ADP 519	Cranberry
ADP 610	Cranberry
ADP 617	Cranberry
ADP 624	Cranberry
ADP 643	Cranberry
ADP 660	Cranberry
ADP 661	Cranberry
ADP 663	Cranberry
ADP 677	Cranberry
BWINDI	Red speckled
GADRA	Red speckled
MBOMVV	Red speckled
ORIBI	Red speckled
UKULINGA	Red speckled

3.2.2 Description of the experimental sites

The genotypes were evaluated under field conditions at Ukulinga and Potchefstroom Research Farms during the 2016/17 growing season. Potchefstroom is located in the North West province of South Africa (26^{0}S’ 27^{0}E’) at 1349 meters above sea level (masl), while Ukulinga is located in KwaZulu-Natal province (29^{0}S’ 40^{0}E’) at 806 masl. Based on climatic data, Ukulinga has an average annual temperature and rainfall of 18.0^{0}C and 738 mm respectively (Mwadzingeni et al., 2016), while Potchefstroom has an average annual temperature of 18.1^{0}C and an annual rainfall of 500 mm. The two sites receive a seasonal rainfall from October to May, and the actual weather data for the period of study for the two sites is presented in the Table 3.2.

Table 3.2 Weather data for Potchefstroom and Ukulinga for 2016/17 growing season

Month	Potchefstroom			Ukulinga		
	Min Temp (^{0}C)	Max Temp (^{0}C)	Rainfall (mm)	Min Temp (^{0}C)	Max Temp (^{0}C)	Rainfall (mm)
November	15.5	29.7	94.7	14.7	23.0	76.0
December	17.0	32.6	94.0	13.7	38.5	33.0
January	16.5	28.4	29.2	11.6	37.9	70.0
February	16.8	26.5	225.6	14.5	36.6	94.0
March	14.7	27.9	33.8	11.7	37.2	32.3
April	10.4	25.4	46.2	7.8	36.4	36.6
May	4.9	22.6	10.7	7.2	30.8	56.9
June	2.5	22.1	0.0	6.0	28.0	1.0
Average	12.3	26.9	66.8	10.9	33.8	53.8
Total			534.2			453.5

Min temp- minimum temperature, Max temp- maximum temperature

3.2.3 Experimental design

The genotypes were evaluated in a 10 × 3 alpha lattice design with three replications at each site. The experimental units were two row plots of 4 m in length with an inter row and intra row spacing of 0.75 m and 0.075 m, respectively.

3.2.4 Trial establishment and management

Potchefstroom has a clay-loam soil texture (Snijman et al., 2014) while Ukulinga has a predominantly clay soil texture (Jarvie and Shanahan, 2008). Both sites were disked prior to planting to attain a fine tilth. The trial in Potchefstroom was planted on 19 December, 2016 while the one at Ukulinga was planted on 17 February, 2017. All agronomic practices that included fertilizer application, herbicide and insecticide applications were applied based on the local recommendations (Department of Agriculture, 2011). The trial in Potchefstroom was planted using a mechanised planter while the one at Ukulinga was hand planted. Hand weeding was done in between rows and plants until the canopy developed to supress the weeds. Harvesting was done by hand pulling and threshing by beating with sticks.

3.3 Data collection

Data was collected on eleven traits among which were architectural, phenological and yield traits. Architectural traits included; the upright plant score (UPS), plant height (PH), stem diameter (SD), first pod insertion height (FPIH), lodging (LDG), shattering (SHT) and number of branches (NB). The days to physiological maturity (DPM) was the only phenological trait, while yield traits included number of the pods per plant (PPP), seed weight (SW) and seed yield (Y). The upright plant score was collected based on the plant architecture grade outlined by Collicchio et al. (1997), where score 1 represents an upright single stem with high pod clearance from the soil surface, score 2 represents an upright plant with some ramification and high pod clearance, score 3 represents an upright plant with some ramification and low pod clearance, score 4 represents an upright plant with many ramifications and a tendency to prostrate and finally, score 5 represents a plant with long internodes and very prostrate. The plant height was measured as the length of the central axis from the soil surface to the tip of the vine in centimetres at maturity. The stem diameter was measured using a Vernier callipers, in mm at maturity right above the soil surface. The first pod insertion height was measured in centimetres from soil surface to first pod insertion. The number of branches was determined by counting the number of basal branches at maturity. Shattering was observed and recorded as either shattering (score 2) or non- shattering (score 1) at harvesting maturity. Lodging was observed and recorded by assigning ratings at harvesting maturity, score 1 represented an upright plant, while score 9 represented a prostrate plant. The days to maturity were determined as the number of days from planting date to the date when 80% of the pods and leaves had dried. The number of pods per plant was determined by counting the total number of pods in the whole plant at maturity. The seed weight data was measured by counting and weighing hundred seeds in grams; and finally seed yield was determined as the weight of all seed per plot at harvesting in t ha^{-1}. The plant height, stem diameter, first pod insertion height, number of pods per plant and number of branches per plant were measured from a sample of ten plants per plot, while the other traits were collected on a per plot basis.

3.4 Data analysis

Data for each trait was subjected to analysis of variance (across sites) following the unbalanced design procedure of Genstat® version 18 (Payne, 2014). In the model, replications and blocks nested in a replicate were considered as random terms, whilst the genotypes were fixed terms. The model used for data analysis was as follows:

$$Y_{ijk} = \mu + \alpha i + \rho j + \beta jk + \varepsilon ijk$$

Where: Y_{ijk} = the effect of the i^{th} genotype in the k^{th} incomplete block in the j^{th} replicate; αi = effect of the i^{th} genotype; ρj = effect of the j^{th} replicate; βjk = effect of j^{th} replicate and k^{th} incomplete block; εijk = error term of the i^{th} genotype, in the k^{th} incomplete block in the j^{th} replicate.

Means were separated using Fisher's protected least significant differences at 5% level of significance. To determine the magnitude of relationships among the traits, Pearson's rank correlation coefficients (r) were calculated using SPSS version 23 (SPSS, 2012). The principal component analysis was carried out in SPSS based on the correlation matrix to identify traits with great influence for selection. Finally, a principal component biplot was plotted in Genstat to group related genotypes based of the traits of influence.

3.5 Results

3.5.1 Analysis of variance for traits across sites

Eleven traits were measured across two sites, to assess the differences among genotypes in relation to their suitability to direct harvesting. The analysis of variance is shown in Table 3.3. The genotypes showed highly significant differences ($p \leq 0.001$) on all the traits except for the number of branches which showed moderately significant differences ($p \leq 0.05$). Site exhibited highly significant differences ($p \leq 0.001$) on days to physiological maturity, stem diameter, plant height, number of pods per plant, seed weight, upright plant score, yield, number of branches per plant and the first pod insertion height, while it was non-significant on lodging and shattering. The genotype by sites interaction highly effected ($p \leq 0.001$) the days to physiological maturity, lodging, plant height and moderately ($p \leq 0.05$) on seed weight. The rest of the traits showed no interaction.

Table 3.3 Mean squares and significance test of eleven traits after combined analysis of variance across two sites

Source of Variation	DF	DPM	SD	LDG	PH	PPP	SW	UPS	Y	NB	FPIH	SHT
Block	2	18.07ns	0.74ns	11.11**	95.96ns	21.05ns	24.57ns	0.09ns	0.31ns	0.10ns	46.73***	0.12ns
Incomplete blocks	6	107.43***	0.54ns	4.97*	154.92***	10.39ns	156.82***	0.48**	0.21ns	0.63ns	16.06**	0.04ns
Genotype	29	216.81***	3.31***	15.55***	464.33***	32.45***	215.97***	1.58***	0.46***	1.15*	28.57***	0.69***
Site	1	417.09***	64.08***	0.67ns	10805.05***	1555.85***	3247.85***	1.8***	5.74***	23.54***	896.46***	0.09ns
Genotype× Site	29	86.78***	1.06ns	6.62***	128.18***	14.86ns	19.82*	0.2ns	0.25ns	0.71ns	0.45ns	0.09ns
Residual	112	13.09	0.82	1.93	39.76	10.24	11.43	0.14	0.18	0.75	4.79	0.08
Total	179	63.51	1.61	5.10	187.5	23.35	69.03	0.40	0.27	0.92	13.77	0.18

DF-degrees of freedom, DPM- days to maturity, SD-stem diameter, LDG- lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB-number of branches per plant, FPIH-first pod insertion height and SHT-shattering

3.5.2 Mean performance of cultivars for various traits

Table 3.4 presents the means, the standard error of differences (SED), least significant differences (LSD) at 5% level of significance and the coefficient of variation (CV) for all traits measured. It further lists genotypes based on the upright plant score from the most upright cultivar to the most prostrate. The top thirteen cultivars had an upright plant score above the population mean, indicating suitability for direct harvesting. Significant differences were observed in the overall genotype mean for different traits measured. The mean for days to physiological maturity was 76.6, with the earliest maturing cultivar ADP 470 recording 64.2 days while the latest was Ukulinga with 90.3 days. The mean stem diameter was 6.9 mm, ADP 455 had the thickest stems with a diameter of 8.3 mm, while ADP 180 was the thinnest with a diameter of 5.7 mm. The mean lodging score was 3.4, and ADP 242 was the most tolerant to lodging with a score of 1.7, while ADP 180 was the most susceptible with a score of 8.3. The mean plant height was 53.4 cm and the tallest genotype was ADP 180 with a height of 79.4 cm, while the shortest was ADP 435 with a height of 42.2 cm. A mean of 11.7 pods per plant was obtained, with Mbomvu having the highest number of pods per plant of 16.1 and ADP 677 with the lowest number of pods of 7.9 per plant. The mean seed weight was 51.5 g, Mbomvu had the largest seeds at 61.1 g per hundred seeds, and ADP 435 the smallest with a weight of 38.4 g per hundred seeds. The highest seed yield was recorded for ADP 36, ADP 35, Ukulinga and Mbomvu at 1.9 t ha^{-1}, while ADP 661, Gadra and ADP 663 had the lowest yield at 1.1 t ha^{-1}. The mean yield was 1.5 t ha^{-1}. The mean number of branches recorded per plant was 3.8; Oribi recorded the highest number of 4.9 branches per plant and ADP 180 the lowest number at 2.8 branches per plant. The mean first pod insertion height recorded was 15.7 cm and the highest was recorded in ADP 436 at 19.9 cm and ADP 435 the lowest at 11.3 cm from the ground. Seventeen genotypes with a score of one were non-shattering and these included ADP 435, Gadra and Ukulinga, while the rest were shattering (score 2).

Table 3.4 Trait means for genotypes evaluated and listed from the most upright to the most prostrate using upright plant score.

Genotype	DPM	SD	LDG	PH	PPP	SW	UPS	Y	NB	FPIH	SHT
ADP 35	80.8	7.2	2.5	55.1	10.3	54.4	2.0	1.9	3.9	16.7	1.0
ADP 166	81.2	7.3	2.7	56.7	11.1	52.5	2.2	1.6	3.8	19.4	1.0
ADP 211	82.8	7.6	3.5	56.5	12.8	55.0	2.2	1.7	3.9	18.2	1.0
ADP 36	82.7	7.8	2.5	55.2	12.5	55.3	2.2	1.9	3.9	18.2	1.2
ADP 395	75.2	8.0	2.8	52.6	10.3	54.7	2.2	1.7	4.0	16.6	1.0
ADP 436	83.0	7.4	3.8	56.3	14.2	57.0	2.2	1.5	4.0	19.9	1.0
ADP 455	85.3	8.3	4.0	61.3	13.6	51.4	2.2	1.6	3.8	19.0	1.0
UKULINGA	90.3	8.2	1.7	54.2	14.5	56.4	2.5	1.9	4.8	12.8	1.0
ADP 458	86.5	7.8	2.5	55.4	13.7	51.4	2.7	1.7	4.2	14.4	1.0
ADP 515	78.2	6.9	2.3	48.3	14.9	42.6	2.7	1.8	4.4	13.7	1.0
ADP 617	70.2	6.1	4.0	44.8	7.9	55.1	2.7	1.3	3.4	15.9	1.7
ADP 661	69.8	7.3	3.5	51.5	9.0	51.9	2.7	1.1	3.6	19.0	2.0
MBOMVV	82.2	7.4	2.2	49.7	16.1	61.7	2.7	1.9	4.2	15.4	1.0
ADP 208	75.8	7.2	3.7	51.3	10.4	55.4	2.8	1.7	4.1	17.9	1.5
ADP 437	78.8	6.4	1.8	49.9	10.0	52.0	2.8	1.6	3.9	13.1	1.0
ADP 624	72.7	6.9	4.3	47.7	12.3	59.1	2.8	1.5	3.5	16.6	1.8
ADP 677	70.2	6.9	2.0	43.1	7.9	56.5	2.8	1.3	3.6	14.9	1.8
BWINDI	77.2	6.9	2.5	46.4	10.7	49.1	2.8	1.4	3.7	15.9	1.2
ORIBI	82.3	8.0	1.8	51.7	11.1	54.7	2.8	1.5	4.9	12.9	1.0
ADP 242	69.7	6.2	1.7	44.4	9.8	55.2	3.0	1.5	3.3	15.8	2.0
ADP 435	74.3	6.5	1.7	42.2	12.3	38.4	3.0	1.2	4.3	11.3	1.0
ADP 610	74.2	6.4	2.3	46.6	13.2	38.5	3.0	1.8	3.7	16.8	1.0
ADP 643	70.3	6.3	5.5	48.8	9.8	56.9	3.0	1.2	3.7	17.3	1.7
ADP 660	69.0	6.7	6.3	54.5	8.8	56.9	3.0	1.2	3.8	16.2	1.3

Genotype	DPM	SD	LDG	PH	PPP	SW	UPS	Y	NB	FPIH	SHT
GADRA	71.0	6.6	3.3	44.5	10.9	43.7	3.0	1.1	3.8	12.0	1.0
ADP 663	72.7	6.3	3.3	45.8	8.9	49.5	3.2	1.1	3.4	14.6	1.5
ADP 519	74.8	7.2	5.0	69.2	15.1	40.5	3.5	1.6	3.5	15.4	1.0
ADP 434	79.7	6.0	6.7	70.7	16.0	41.4	3.8	1.8	3.5	12.9	1.2
ADP 180	72.0	5.6	8.3	79.4	10.5	53.8	4.0	1.3	2.8	14.4	1.0
ADP 470	64.2	5.6	4.5	69.3	12.7	43.5	4.0	1.3	3.1	15.0	1.2
Grand Means	76.6	6.9	3.4	53.4	11.7	51.5	2.8	1.5	3.8	15.7	1.2
SED	2.10	0.50	0.80	3.60	1.90	2.00	0.10	0.25	0.50	1.30	0.20
LSD (5%)	4.13	1.03	1.59	7.21	3.66	3.87	0.42	0.49	0.99	2.50	0.32
CV (%)	4.40	13.00	40.60	11.80	27.30	6.50	13.10	28.00	22.70	13.90	23.00

DPM- days to maturity, SD- stem diameter (mm), LDG- lodging, PH- plant height (cm), PPP- number of pods per plant; SW- seed weight (g), UPS- upright plant score, Y- seed yield (t ha^{-1}), NB- number of branches per plant, FPIH- first pod insertion height (cm) and SHT- shattering

3.5.3 Correlations among traits

The correlation coefficients describing the degree of relationships amongst traits measured are presented in Table 3.5. The analysis showed that days to physiological maturity had a strong positive correlation with the stem diameter (r = 0.73), yield (r = 0.69), number of branches (r = 0.66) and pods per plant (r = 0.57), but was negatively correlated to upright plant score (r = -0.56) and shattering (r = -0.58). The stem diameter showed a positive relationship with the number of branches (r = 0.69) and yield (r = 0.45), but was negatively correlated with lodging (r = -0.44) and upright plant score (r = -0.75). Lodging had a positive correlation with plant height (r = 0.69) and upright plant score (r = 0.56) however, lodging was negatively correlated with the number of branches per plant (r = -0.60). Plant height was positively correlated with the number of pods per plant (r = -0.39) and upright plant score (r = 0.42) however, it was negatively correlated with the number of branches per plant (r = -0.37) and shattering (r = -0.37). The number of pods per plant was strongly correlated with yield (r = 0.62) and was negatively correlated with shattering (r = -0.37). The seed weight was positively correlated with first pod insertion height (r = 0.42) and negatively correlated with upright plant score (r = -0.45). The upright plant score was negatively correlated with the number of branches per plant (r = -0.53) and first pod insertion height (r = -0.51).Yield had a positive correlation with number of branches per plant (r = 0.40) and was negatively correlated with shattering (r = -0.44). Finally, the number of branches per plant showed a negative correlation with shattering (r = -0.40).

Table 3.5 Pearsons' correlation coefficients between measured traits

Trait	DPM	SD	LDG	PH	PPP	SW	UPS	Y	NB	FPIH	SHT
DPM	1										
SD	0.73**	1									
LDG	-0.35	-0.44*	1								
PH	0.12	-0.10	0.69**	1							
PPP	0.57**	0.27	-0.01	0.39*	1						
SW	0.19	0.35	-0.03	-0.14	-0.31	1					
UPS	-0.56**	-0.75**	0.56**	0.42*	0.04	-.45*	1				
Y	0.69**	0.45*	-0.29	0.20	0.62**	0.07	-0.36	1			
NB	0.66**	0.69**	-0.60**	-0.37*	0.33	0.11	-0.53**	0.40*	1		
PIH	0.07	0.31	0.11	0.08	-0.11	0.42*	-0.51**	0.12	-0.20	1	
SHT	-0.58**	-0.29	0.07	-0.37*	-0.58**	0.33	0.12	-0.44*	-0.40*	0.22	1

**Correlation is significant at the 0.01 level, *correlation is significant at the 0.05 level. DPM-days to maturity, SD-stem diameter, LDG-lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB-number of branches per plant, FPIH-first pod insertion height and SHT-shattering

3.5.4 Principal component analysis

In order to quantify the variations due to the measured traits on the genotypes, and to further separate genotypes by grouping, a principal component analyses was carried out (Table 3.6). The analyses showed that three principal components were important, accounting for 78.55% of the total variation. However, the principal component 1 (PC-1) and principal component 2 (PC-2) had more influence, accounting for a cumulative 62.44% of total variation in the data set. The total variation of PC-1 (38.52%) was mainly contributed by six traits namely days to physiological maturity, number of pods per plant, yield, stem diameter, plant height and the number of branches per plant. The variation accounted by PC-2 (23.92%) was mainly contributed by lodging and the upright plant score. The variation accounted for by PC-3 (16.11%) was contributed mainly by the first pod insertion height, seed weight and shattering, while 21.45% was unexplained.

Table 3.6 Eigenvalues and principal component from correlation matrix of traits

Trait	PC-1	PC-2	PC-3
DPM	0.85	-0.29	0.27
PPP	0.83	0.14	-0.22
SHT	-0.80	-0.01	0.27
Y	0.78	-0.10	0.19
SD	0.57	-0.45	0.53
LDG	-0.13	0.90	-0.01
PH	0.43	0.85	-0.02
NB	0.53	-0.73	0.02
FPIH	-0.03	0.21	0.85
SW	-0.13	-0.11	0.79
UPS	-0.27	0.58	-0.68
Explained variance (Eigenvalue)	4.24	2.63	1.77
Proportion of total variance (%)	38.52	23.92	16.11
Cumulative variance (%)	38.52	62.44	78.55

PC-1- principal component 1, PC-2-principal component 2, PC-3-principal component 3, DPM-days to maturity, SD-stem diameter, LDG-lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB-number of branches per plant, FPIH- first pod insertion height and SHT-shattering

The principal component biplot (Figure 1) was used to separate genotypes based on traits with high positive loading in principal components 1 and 2. Traits are represented by dimensional vectors, whereby the smaller angles between vectors running in the same direction shows a strong correlation between the traits. The upright plant score and lodging, and the first pod insertion height and seed weight were strongly correlated. Genotypes superior in a particular trait were plotted close to the vector line and further in the direction of the vector. However, some traits such as lodging, upright plant score and shattering are in the opposite direction of the vector. The principal component 1, defined by days to physiological maturity, pods per plant, yield, plant height and stem diameter, respectively, had on its positive section a cluster of genotypes such as Ukulinga, ADP 455, ADP 458, Mbomvu, ADP 515, ADP 211, ADP 35, Oribi, ADP 395, ADP436, ADP166 and ADP 437. These genotypes also had a low upright score, which is important for direct harvesting. However, genotypes such as ADP 180, ADP 470, ADP 519 and ADP 434 were clustered in the extreme positive end of PC 2, which was mainly defined by lodging and the upright plant score.

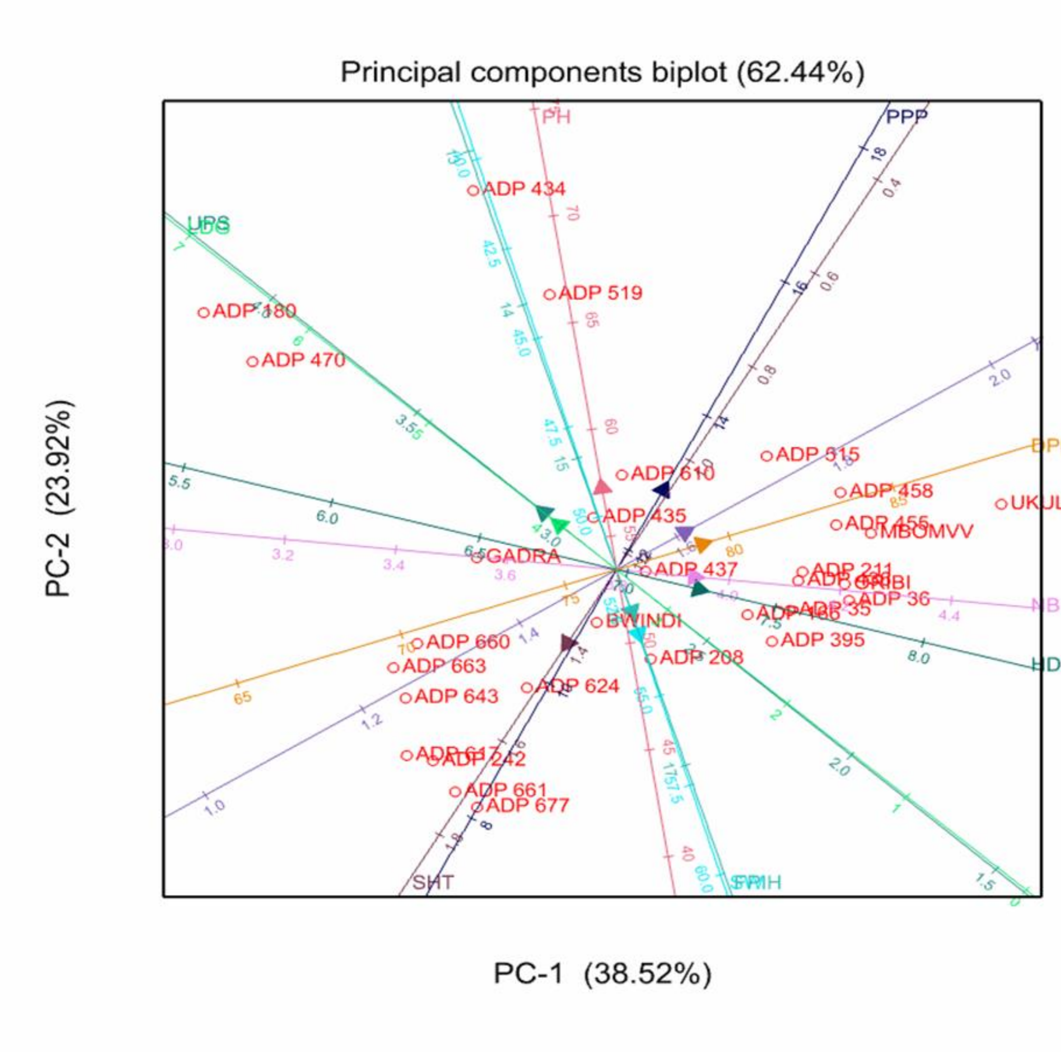

Figure 3.1 Principal components biplot showing genotypic grouping

PH- plant height, HD- stem diameter, SHT- shattering, FPIH first pod insertion height, Y-yield, SW- seed weight, PPP- pods per plant, NB- number of branches per plant, LGD- lodging, UPS- upright plant score and DPM- days to physiological maturity.

3.6 Discussion

The upright bean architecture suitable for direct harvesting is a complex trait, which is determined by a number of morphological traits that may include among others the stem diameter, plant height, number and angle of branches, first pod insertion height, pod distribution on the main stem, canopy porosity, growth habit, lodging and shattering (Silva et al., 2013). Even though the trait can be evaluated as a whole visually using the upright plant score (Collicchio et al., 1997), its breeding improvement follows the ideotype breeding approach (Donald, 1968). This breeding approach seeks to improve a complex trait through identifying and improving component traits, which may be easy to breed for. Various researchers used morphological and agronomical traits to evaluate upright plant architecture such as Kelly (2001), Moura et al. (2013) and Silva et al. (2013). This study evaluated architectural traits that contribute to the upright bean architecture as well as the overall score of uprightness on thirty Type I cultivars from the Andean genepool. This study focussed on identifying possible parents for the breeding for an upright architecture and its related traits for suitability of direct harvesting, as well as determining the relationships between the morphological traits.

Highly significant differences were observed for all the traits studied (combined analysis), except for the number of branches which showed moderate significant differences. The studied traits were highly diverse. Similar results were reported by Moura et al. (2013) in their study of the potential of morphological traits in evaluating plant architecture. Sites showed highly significant differences ($p \leq 0.001$) on days to physiological maturity, stem diameter, plant height, number of pods per plant, seed weight, upright plant score, yield, number of branches per plant and the first pod insertion height, indicating environmental conditions differed between the two sites. A strong genotype by site interaction observed on the days to physiological maturity, lodging, plant height and seed weight shows the influence of the combined effect of the environment and the genotype on the expression of the traits. Similar results were reported by Soltani et al. (2016). However, a lot of genetic advance would be realised in improving stem diameter, number of pods per plant, the upright plant score, seed yield, number of branches per plant, the first pod insertion height and shattering because they were not affected by the environment. The results are similar to what was reported by (Moura et al., 2013).

The study showed that a number of genotypes possessed the upright architecture suitable for direct harvesting as observed from the grand mean for the data set. The data set was quite diverse in the trait with the score ranging from 2 to 4. However, thirteen genotypes namely ADP 35, ADP 166, ADP 211, ADP36, ADP 395, ADP 436, ADP 455, Ukulinga, ADP458, ADP 515, ADP 617, ADP 661 and Mbomvu, showed an upright score below the mean and could be considered for selection for the improvement of suitability to combine harvesting in dry bean. Similar to what was reported by Moura et al. (2013), the cultivars that had a low upright score were characterised with thicker stems, taller plants and a lower lodging score, except for ADP 455 and ADP 617 which recorded a lodging score of 4 indicating about 40% susceptibility to lodging. The genotypes ADP 455 and ADP 617, had the thickest stems among those with a low upright score. However the high lodging percentage could be attributed to the height of plants which was way above the mean.

The first pod insertion height showed a lot of variation in the data set ranging from 11.3 to 19.9 cm, with a mean of 15.7 cm. This trait is of importance in the breeding for suitability to combine harvesting because pods are raised high above the ground, thereby reducing combine header losses and preventing pods from touching the ground. Sixteen genotypes, namely ADP 35, ADP 166, ADP 211, ADP 36, ADP 395, ADP 436, ADP 455, ADP 617, ADP 661, ADP 208, ADP 624, Bwindi, ADP 242, ADP 610, ADP 643 and ADP 660, were found to have a first pod insertion height higher than the data set mean, hence could be considered for the improvement of the trait. Kelly (2001), stressed the importance of stem diameter in breeding for suitability to combine harvesting as to thick stems that would resist lodging, thereby reducing losses due to the falling plants. The data set was diverse in stem diameter, having mean of 7 mm and a range of 5.6 to 8 mm. The mean stem diameter was slightly higher than what was reported by Soltani et al. (2016). This could be attributed to the differences in the properties of the data sets used. However, genotypes ADP 35, ADP 166, ADP 211,ADP 36, ADP 395, ADP 436, ADP 455, Ukulinga, ADP 458, ADP 661, Mbomvu, ADP 208 and ADP 519 were found to have a diameters higher than the data set mean and therefore, they can be considered in the breeding for improvement of stem diameter. The days to physiological maturity is important in determining the earliness or lateness of a cultivar to mature. However the most important property in relation to combine harvesting is uniformity in maturity, because the combine does not thresh immature pods resulting in losses (Kelly, 2001). Days to maturity in the data set ranged from 64.2 in ADP 470 to 90.3 in Ukulinga. The plant height is important for the upright architecture. Acquaah et al. (1991), defined the suitable plant height for suitability to combine harvesting as ranging from 50 to 55 cm. The mean for the data set was 53.4 cm and the range was from 43.1 to 79.4 cm. A number of cultivars were found to have a height higher than the mean and these were ADP 470, ADP 180, ADP 519, ADP 660, ADP 436, ADP 36, ADP 211, ADP 166 and ADP35. Combine harvesting requires plants to be standing up straight for them to be picked by the combine, therefore those susceptible to lodging are not desired because they result in harvest losses. A large variation was observed for lodging in the data set ranging from a score of 1.7 to 8.3 (11.7 to 83% lodging) and the mean was 3.4 (34% lodging). A number of genotypes, namely ADP 663, Gadra, ADP 610, ADP 435, ADP 242, Oribi, Bwindi, ADP 677, ADP 437, Mbomvu, ADP 515, ADP 458, Ukulinga, ADP 395, ADP 36, ADP 166 and ADP 35 were found to have a lodging score lower than the mean score for the data set. These genotypes could be considered for the improvement of the trait, however, selection should be done under several environments because the trait was influenced by the environment. Shattering is another trait not desired in breeding for suitability to combine harvesting. Seventeen genotypes were found to be non-shattering, namely ADP 35, ADP 166, ADP 211, ADP 395, ADP 436, ADP 455, Ukulinga, ADP 458, ADP 515, Mbomvu, ADP 437, Oribi, ADP 435, ADP610, Gadra, ADP 519 and ADP 180.

The yield and yield related traits were also very diverse in the data set as observed from the number of pods per plant which ranged from 7.9 to 16.1 with a mean of 11.7. Most of the genotypes were large seeded with mean of 51.5 g per hundred seed, and corresponding to the preferred market class in South Africa (Department of Agriculture, 2011). The mean for seed yield in the data set was 1.5 t ha^{-1} and ranged from 1.1 to 1.9 t ha^{-1}. Most of the cultivars were high yielding and may be used to improve seed yield for suitability to combine harvesting. The cultivars with the yield higher than the mean included ADP 663, Gadra, ADP 610, ADP 435, ADP 242, Oribi, Bwindi, ADP 677, ADP 437, Mbomvu, ADP 515, ADP 458, Ukulinga, ADP395, ADP 36, ADP 166 and ADP 35. The mean seed yield was less than the 2.6 t ha^{-1}, reported by Soltani et al. (2016). This could be attributed to the fact the data set comprised of only Type I genotypes compared to Types I, II, IIa and III used by Soltani et al. (2016).

Understanding the correlations between traits allows the breeders to carry out simultaneous selections of characters associated with desired traits for improvement (Kumar et al., 2012). The days to physiological maturity, stem diameter, seed weight, number of branches and first pod insertion showed significant negative correlation with the upright architecture score, while lodging and plant height showed a positive correlation. These results are similar to what was reported by Silva et al. (2013). Selecting for thicker stems would improve the upright architecture suitable for direct harvesting. Similar findings were also reported by Adams (1982). However, it would be important to define an optimum plant height that would improve the upright architecture, while minimizing lodging for it to be effectively used in selection. A negative relationship was observed between stem diameter and lodging, signifying that selecting thicker stems would reduce lodging, which is in agreement with what was reported by Oliveira et al. (2015). Improving yield is the ultimate goal of every plant breeding programme. A weak negative correlation was observed between yield and upright plant architecture, implying that the upright architecture in a cultivar can be improved without affecting its yield potential, similar to what was reported by (Alvares et al., 2016). However, an important positive correlation was also observed between stem diameter and yield. This relationship means that selecting for thicker stems would indirectly improve seed yield

(Oliveira et al., 2015). Stem diameter is one of the traits highly correlated with upright architecture, and therefore, the breeder may use stem diameter in a breeding programme for suitability to combine harvesting to improve the upright plant architecture, while indirectly improving seed yield. Similar results were also reported by Soltani et al. (2016) in their study of interrelationships between architectural traits in dry bean. The weak positive correlation observed between plant height and yield would mean than a breeder can manipulate the plant height to an optimum which would significantly reduce lodging without affecting yield potential of a cultivar.

The principal component analysis is a multivariate tool that is useful in identifying a set of traits with greater influence in defining a given data set (Johnson, 1998). Using the method outlined by Chatfield and Collins (1980), where only eigenvalues above one are considered significant, three principal components were extracted explaining a total variation of 78.55% of the data set. However, principal components 1 and 2 were more influential in explaining the variation in the data set, accounting for 38.52% and 23.92% respectively. Hair et al. (1998), stated that, factor loadings that are greater than ±0.3 are considered to have a meaningful contribution towards the variation explained by a particular principal component. Factor analysis showed that the variation explained by the first principal component were due to days to physiological maturity, number of pods per plant, seed yield, stem diameter, plant height and the number of branches per plant. The results agree with Adams (1982) findings that outlined the importance of stem diameter and plant height in selecting for upright plant architecture in dry bean. The variation explained by the second principal component was due to lodging and the upright plant score. Though not influential, the 16.1% variation explained by the third principal component was contributed by shattering, the first pod insertion height and seed weight. Traits with high positive loading in the first principal component should be given first priority for selection when improving suitability to combine harvesting followed by those loaded in the second principal component. The principal component biplot was used to separate genotypes based on the traits that contributed to the variations in principal component 1 and 2. This may allow a breeder to decide on best genotypes to select based on variables of interest (Ali et al., 2011). Smaller angles between vectors running in the same direction indicate a strong correlation between traits while genotypes superior in a particular trait were plotted close to a vector line and further in the direction of a vector (Mwadzingeni et al., 2016).

3.7 Conclusion

The analysis of variance revealed great variations among genotypes for the eleven traits evaluated. It also showed the presence of environmental influence in the expression of the days to physiological maturity, lodging, plant height and seed weight. The study identified superior genotypes based on the mean for each of the eleven traits evaluated. The superior genotypes may be utilized through the ideotype breeding approach to improve the suitability of dry bean to direct harvesting. The correlation analysis revealed the importance of stem diameter for simultaneous selections of traits such as the upright plant score, seed yield, days to physiological maturity and lodging. It was observed that selecting for thicker stems would improve the upright plant architecture as a whole, reduce lodging, increase the days to physiological maturity and also improve yield. Furthermore, it was observed through factor analysis that apart from the number of pods per plant and seed yield, the stem diameter and plant height were very important traits to be considered for selection when improving suitability to combine harvesting in the data set. Therefore, genotypes ADP 35, ADP 166, ADP 211, ADP 36, ADP 395, ADP 436, ADP 455, ADP 458, ADP 661, Mbomvu and Ukulinga that were found to have thicker stem diameters and non-shattering, may be useful in improving both seed yield and the upright architecture suitable for combine harvesting.

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Chapter 4

Estimation of the phenotypic and genotypic variability, heritability, and genetic gain of traits related to direct harvesting in dry bean

Abstract

The magnitude of genetic variability plays a vital role in the success of any crop improvement programme. The upright bean architecture, suitable for direct harvesting, is only found among Type I and II growth habits. This study aimed at estimating the phenotypic variance, genotypic variance, heritability and the expected genetic gain from selection to provide information that could be used in the improvement of upright bean architecture suitable for direct harvesting. Thirty Type I genotypes from Andean gene pool were used in the study and were laid out in a 10×3 alpha lattice design with three replications at the Agriculture Research Council in Potchefstroom, and at Ukulinga Research Farm in Pietermaritzburg, South Africa. Data was collected on the upright plant score, stem diameter, first pod insertion height, lodging, shattering, number of branches, days to physiological maturity, number of pods per plant, seed weight and seed yield. The analysis of variance showed highly significant differences among genotypes, indicating the presence of genetic variability in the data set. The site was also significant, indicating environmental differences in terms of growing conditions. Significant interaction of genotype with the site was observed on days to physiological maturity, lodging, plant height and seed weight. The phenotypic coefficient of variation was slightly higher than the genotypic coefficient of variation for all traits, showing little environmental influence on the expression of traits. Generally, a high variability was observed in the population. Broad sense heritability estimates ranged from moderate (30% $\geq H^2 \leq$ 60%) to high ($H^2 \geq$60%), except for the number of branches per plant, which recorded a low heritability value of 29%. The moderate to high heritability and expected genetic gains observed in the population could be exploited through selection and hybridisation during the improvement of the upright bean architecture suitable for direct harvesting.

Keywords: Direct harvesting, dry bean, genetic gains, morphological traits, upright architecture.

4.1 Introduction

The upright bean architecture suitable for direct harvesting is defined by a number of morphological traits that includes, the growth habit, plant height, stem diameter, number and angle of branches, number and distribution of pods, length of internodes and first pod insertion height (Teixeira et al., 1999). The morphological traits defining upright bean architecture play an important role in its expression, hence, breeders use them for germplasm evaluation. The upright bean architecture as a whole is evaluated using a grade scale outlined by Collicchio et al. (1997). This type of evaluation is visual and requires a lot of experience. Breeders often use morphological traits to study upright plant architecture in dry bean (Adams, 1973, Adams, 1982, Kelly and Adams, 1987). Other studies prioritise the growth habit, plant height, stem diameter, number and angle of branches, first pod insertion height, and number and distribution of pods as the major determinants of the upright bean architecture suitable for direct harvesting.

The improvement of the upright architecture suitable for direct harvesting through morphological traits is highly dependent on the magnitude of genetic variability of the traits in a given population (Idahosa et al., 2010). The magnitude of genetic variability is important in determining selection response in a population. The genetic variability, heritability and genetic advance are specific to a given population. However, the expression of these parameters may be affected by the environment (Raje and Rao, 2000, Kavera, 2008). Generally, phenotypic expression of a trait is a result of the genetic constitution of the plant and the environment in which it is raised. In order to successfully improve the trait, it is important for the breeder to partition the phenotypic variability observed, into heritable and non- heritable components. This can be done by estimating the phenotypic and genotypic coefficients of variation, heritability and genetic advance (Hiremath, 2009).

Knowledge of heritability of a trait helps the breeder to have an idea of the extent to which genetic factors control trait expression (Chopra, 2000). It further shows the reliability of phenotypic variability observed in a selection programme. Traits with high heritability estimates are easy to select for, and genetic gain is achieved in a short period of time. Broad sense heritability is estimated as a ratio of the genetic variance to the phenotypic variance, hence, traits with high heritability are more easily improved by selection and breeding than those with low heritability (Jibrin and Habu, 2016).

The manual or mechanical pulling into windrows followed by threshing harvesting system of Type III beans, requires a lot of labour and time. A number of bean producers are now preferring direct harvesting as a cost effective method of harvesting dry bean (Soltani et al., 2016). However direct harvesting require a suitable cultivar to maximise benefits (Nowatzki, 2013). A suitable upright architecture is made up of a number of morphological traits. This study was, therefore, aimed at estimating phenotypic and genetic variability, heritability and genetic advance for morphological traits (architectural traits), to provide information that may be useful in the improvement of the upright architecture suitable for combine harvesting in dry bean.

4.2 Materials and methods

4.2.1 Site

This study was carried out at Potchefstroom located in the Northwest Province of South Africa (26^0S’ 27^0E’) at 1349 meters above sea level (masl) and at Ukulinga Research Farm (29^0S’ 40^0E’) located in the KwaZulu-Natal Province at 806 masl. Potchefstroom has a clay-loam soil texture (Snijman et al., 2014), while Ukulinga has a predominantly clay soil texture (Jarvie and Shanahan, 2008). The weather data during the period of study is as presented in chapter 3 (Table 3.2).

4.2.2 Plant materials

The experimental materials were as outlined in chapter 3 (Table 3.1).

4.2.3 Experimental design and crop establishment

The experiment was laid out in a 10 × 3 alpha lattice design with three replications at each site. A two row experimental unit of 4 m length was used with inter and intra row spacing of 0.75 × 0.1 m at both sites. The trial at Potchefstroom, was planted on 19 December, 2016 using a mechanical planter, while the one at Ukulinga was manually planted on 17 February, 2017. One seed was planted per planting station. Both trials were grown under rain-fed conditions. Agronomic practices such as fertilizer application, herbicide and insecticide applications were applied based on the local recommendations (Department of Agriculture, 2011). Hand weeding was done in between rows and plants until the canopy developed to supress the weeds. Harvesting was done by hand pulling and threshing by beating with sticks.

4.3 Data collection

Data were collected on seven architectural traits, one phenological and three yield traits. Architectural traits included; upright plant score (UPS) measured using a scale of 1-5, where score 1 corresponded to upright single stem with high pod clearance from the soil surface, score 2, an upright plant with some ramification and high pod clearance, score 3 an upright plant with some ramification and low pod clearance, score 4 an upright plant with many ramifications and tendency to prostrate and score 5 a plant with long internodes and very prostrate. The plant height (PH), was measured in cm from the ground to the tip of the vine and stem diameter (SD) was measured in mm at the base of the stem at maturity. The first pod insertion height (FPIH), was measured in cm from the ground to first pod insertion, while lodging (LDG) was scored using a 1-9 visual scale, where 1 was most upright and 9 most prostrate. Shattering (SHT) was scored using 1 for non-shattering and 2 for shattering and the number of branches (NB) were recorded as the total number of basal branches at maturity. The phenological trait observed was days to physiological maturity (DPM), recorded as the number of days from planting to the date when 80% of the leaves and pods start drying and yellowing. Yield traits included the number of pods per plant (PPP), seed weight (SW) measured as weight of 100 seeds in grams and seed yield (Y) measured as the weight of seed harvested from the whole plot. All observations were made on ten randomly selected plants from each entry and replication, except for lodging, shattering and seed yield which were observed on a per plot basis.

4.4 Statistical analysis

The data collected was subjected to analysis of variance using the balance design procedure of Genstat® version 18 (Payne, 2014). A combined analysis of variance was performed and significant means were separated using least significant differences (LSD) at a 5% level of significance (Payne, 2014). In the model, replications and blocks nested in a replicate were considered as random terms, whilst the genotypes were fixed terms. The model used for data analysis was as follows:

$$Y_{ijk} = \mu + \alpha i + \rho j + \beta jk + \varepsilon ijk$$

Where: Y_{ijk} = the effect of the i^{th} genotype in the k^{th} incomplete block in the j^{th} replicate; αi = effect of the i^{th} genotype; ρj = effect of the j^{th} replicate; βjk = effect of j^{th} replicate and k^{th} incomplete block; εijk = error term of the i^{th} genotype, in the k^{th} incomplete block in the j^{th} replicate.

The phenotypic and genotypic coefficients of variation and broad sense heritability, based on a per plot basis, were calculated using the formulae outlined by Singh and Chaudhary (1985). The formulae used is as given in the Table 4.3.

Table 4.1 Formulae used in calculating genetic parameters

Genetic parameter	Formula
Error variance $\left(\sigma_e^2\right)$	$\sigma_e^2 = MS_e$
Genotype × site variance $\left(\sigma_{gs}^2\right)$	$\sigma_{gs}^2 = \frac{MS_{gs} - MS_e}{r}$
Genotypic variance $\left(\sigma_g^2\right)$	$\sigma_g^2 = \frac{MS_g - MS_{gs}}{rs}$
Phenotypic variance $\left(\sigma_p^2\right)$	$\sigma_p^2 = \sigma_g^2 + \sigma_e^2 + \sigma_{gs}^2$
Broad sense heritability $\left(H^2\right)$	$H^2 = \frac{\sigma_g^2}{\sigma_p^2} \times 100$
Phenotypic coefficient of variation $(PCV\%)$	$PCV = \frac{\sqrt{\sigma_p^2}}{Mean} \times 100$
Genotypic coefficient of variation $(GCV\%)$	$GCV = \frac{\sqrt{\sigma_g^2}}{Mean} \times 100$
Genetic advance (GA)	$GA = \frac{\sigma_g^2}{\sqrt{\sigma_p^2}} \times k$ where k=2.06 (selection differential at 5% (Johnson et al., 1955)
Genetic gain (GG)	$GG = \frac{GA}{Mean} \times 100$

MS_g - Mean square genotype, MS_s - mean square site, MS_{gs} - mean square genotype by site and MS_e - mean square error.

The components of variance were calculated from the ANOVA using the expected mean squares (Table 4.4.).

Table 4.2 Skeleton ANOVA and its expected mean squares

Source of Variation	DF	Mean Square(Ms)	Expected Mean Square (EMS)
Genotype	g	MS_g	$\sigma_e^2 + r\sigma_{gs}^2 + rs\sigma_g^2$
Site	s	MS_s	
Genotype × site	gs	MS_{gs}	$\sigma_e^2 + r\sigma_{gs}^2$
Residual	r	MS_e	σ_e^2

DF- degrees of freedom, g - degrees of freedom for genotype, s - degrees of freedom for site, gs - degrees of freedom for genotype by site, r - degrees of freedom error, MS_g - mean square genotype, MS_s - mean square site, MS_{gs} - mean square genotype by site, MS_e -mean square error, σ_e^2 - error variance, σ_{gs}^2 - genotype by site variance, σ_g^2 - genotypic variance.

4.5 Results

The analysis of variance for the measured traits are presented in Table 4.5. Highly significant differences ($p \leq 0.001$) were observed on genotypes for all measured traits except for the number of branches per plant that was moderately significant ($p \leq 0.05$). The site effect was highly significant on days to physiological maturity, stem diameter, plant height, pods per plant, seed weight, upright plant score, yield, number of branches and the first pod insertion height. The interaction between genotypes and site was strongly significant on days to physiological maturity, lodging, plant height and moderately significant for seed weight.

Table 4.3 Mean squares and levels of significance

Source of Variation	DF	DPM	SD	LDG	PH	PPP	SW	UPS	Y	NB	FPIH	SHT
Genotype	29	216.81***	3.31***	15.55***	464.33***	32.45***	215.97***	1.58***	0.46***	1.15*	28.57***	0.69***
Site	1	417.09***	64.08***	0.67ns	10805.05***	1555.85***	3247.85***	1.80***	5.74***	23.54***	896.46***	0.09ns
Genotype× Site	29	86.78***	1.06ns	6.62***	128.18***	14.86ns	19.82*	0.20ns	0.25ns	0.71ns	0.45ns	0.09ns
Residual	112	13.09	0.82	1.93	39.76	10.24	11.43	0.14	0.18	0.75	4.79	0.08

***significant at $p \leq 0.001$, **significant at $p \leq 0.01$and * significant at $p \leq 0.05$. DPM-days to physiological maturity, SD - stem diameter, LDG - lodging, PH - plant height, PPP - pods per plant, SW - seed weight, UPS - upright plant score, Y- seed yield, NB - number of branches per plant, FPIH - first pod insertion height and SHT- shattering.

Table 4.6 presents the components of variance estimated for all traits evaluated across two sites. The phenotypic variance was higher than the genotypic and error variances for all traits. The phenotypic variance ranged from 0.4 for yield to 293.3 recorded for plant height. The highest genotypic variance value was recorded for plant height (224.1) and the lowest was recorded for seed yield at 0.1. The error variance ranged from 0.1 recorded for shattering and upright plant score to 39.8 recorded for plant height. The broad sense heritability estimates varied from 29% recorded for seed yield to 90% recorded for the first pod insertion height.

Table 4.4 Components of variance and heritability of the phenotypic traits of dry bean genotypes from two sites

TRAIT	δ^2e	δ^2g	δ^2gs	δ^2p	H^2 (%)
DPM	13.1	86.7	24.6	124.3	70.0
HD	0.8	1.5	0.1	2.4	62.0
LDG	1.9	6.0	1.6	9.5	63.0
PH	39.8	224.1	29.5	293.3	76.0
PPP	10.2	11.7	1.5	23.5	50.0
SW	11.4	130.8	2.8	145.0	90.0
UPS	0.1	0.9	0.0	1.1	86.0
Y	0.2	0.1	0.0	0.4	41.0
NB	0.8	0.3	0.0	1.0	29.0
FPIH	4.8	18.8	-1.5	22.1	85.0
SHT	0.1	0.4	0.0	0.5	83.0

δ^2e - environmental variance, δ^2g - genotypic variance, δ^2gs - variance due to genotype and site interaction, H^2 - broad sense heritability. DPM - days to physiological maturity, SD - stem diameter (mm), LDG - lodging, PH - plant height (cm), PPP - pods per plant, SW - seed weight (g), UPS - upright plant score, Y - seed yield (t ha^{-1}), NB - number of branches per plant, FPIH - first pod insertion height (cm) and SHT- shattering

Table 4.7 presents the means for the data set, genotypic and phenotypic coefficient of variation, genetic advance and expected genetic gain for the traits evaluated. The genotypic coefficient of variation ranged from 12.2% observed for the days to physiological maturity to 71.1% observed for lodging. The phenotypic coefficient of variation was lowest on the days to physiological maturity at 14.6% and highest for lodging at 89.6%. The expected genetic gain as a percentage of the mean was highest for lodging at 116.2% and was lowest on the number of branches per plant at 16.0%.

Table 4.5 Trait means, genotypic and phenotypic coefficients of variation, genetic advance and expected genetic gain.

TRAIT	MEAN	RANGE	CV (%)	GCV%	PVC%	GA	GG%
DPM	76.6	64.2-90.3	4.37	12.2	14.6	16.0	20.9
HD	7.0	5.6-8.3	13.01	17.6	22.3	2.0	28.7
LDG	3.4	1.6-8.3	40.55	71.1	89.6	4.0	116.2
PH	53.4	42.2-79.4	11.80	28.0	32.1	27.0	50.5
PPP	11.7	7.9-16.1	27.33	29.3	41.4	5.0	42.6
SW	51.5	38.4-61.1	6.53	22.2	23.4	22.4	43.5
UPS	2.8	2.0-4.0	13.07	34.1	37.0	1.8	64.9
Y	1.5	1.1-1.9	28.00	24.6	38.9	0.5	32.1
NB	3.8	2.8-4.9	22.74	14.4	26.7	0.6	16.0
FPIH	15.7	11.3-19.9	13.91	27.5	29.9	8.2	52.2
SHT	1.2	1.0-2.0	22.99	52.1	56.9	1.2	98.1

GVC - genotypic coefficient of variation, PVC - phenotypic coefficient of variation, GA - genetic advance, GG - genetic gain. The trait DPM is days to physiological maturity, SD - stem diameter (mm), LDG - lodging, PH - plant height (cm), PPP-pods per plant, SW - seed weight (g), UPS - upright plant score, Y – seed yield (t ha^{-1}), NB - number of branches per plant, FPIH - first pod insertion height (cm) and SHT- shattering

4.6 Discussion

A thorough evaluation of morphological / architectural traits that contribute to the upright bean architecture plays a major role in the improvement of the crop for suitability to direct harvesting. This study evaluated genetic variance components of morphological and architectural traits that contribute to the upright bean architecture suitable for combine harvesting on thirty Type I genotypes drawn from the Andean gene pool. This study quantified the variability of the morphological and architectural traits, estimated heritability and the expected genetic gains and outlined the breeding implication for the improvement of the upright bean architecture suitable for direct harvesting.

The combined analysis of variance showed high significant differences among genotypes ($p \leq 0.001$), indicating that the genotypes where diverse in terms of the traits measured, these results are in line with what was reported by Moura et al. (2013). The significant differences observed between sites ($p \leq 0.001$) on most traits, except for lodging and shattering, shows that the two testing environments were different from each other in terms of growing conditions. However, only days to physiological maturity, lodging, plant height and seed weight were significantly affected by the interaction of the genotypes with the sites ($p \leq 0.001$), implying the environment plays a role in the expression of the four traits (Soltani et al., 2016). Genotype by environment interaction on these traits was also reported by Pereira et al. (2012). This suggests a need to evaluate genotypes in different environments in order to accurately select genotypes that are tolerant to lodging, have good seed size and a desirable days to physiological maturity.

The genetic variance for all the traits were larger than their corresponding genotype by environment variance, indicating that the genotypic effects were more important in the expression of the traits compared to the interaction. Similar results were reported by Alvares et al. (2016) on hundred seed weight and upright bean architecture. According to Hamdi et al. (2003), the genetic variability observed in the population under study was high for all traits, except for days to physiological maturity, stem diameter and the number of branches per plant which showed moderate variability. The genotypic and phenotypic coefficients of variation were high for most of the traits. Variability is said to be low when the genotypic and phenotypic coefficients of variation are less than 10%, medium when between 10 and 20% and high when above 20% (Hamdi et al., 2003). Traits with a low genotypic and phenotypic coefficients of variation shows a narrow scope of selection and less response, while those with high coefficients of variation show the presence of high variability in the population and a positive response to selection (Zerga et al., 2016). The differences between the genotypic coefficients of variation and phenotypic coefficient of variation are small, indicating minimal environmental influence on the expression of the traits. However, from the observed values of the genotypic coefficient of variation, a relatively high response to selection could be achieved on plant height (28.0%), seed weight (22.2%), lodging (71.1%), first pod insertion height (27.5%), shattering (52.1%), upright plant architecture (34.1%), number of pods per plant (29.3%) and seed yield (24.6%), while the number of branches per plant (14.4%), days to physiological maturity (12.2%) and stem diameter (17.6%) would show a moderate scope for selection.

High heritability estimates show that a population has a large genetic component of variation implying ease of selection (Melo et al., 2004). Medium (30-60%) to high (>60%) broad sense heritability estimates were observed among the traits studied. From the heritability estimates; seed weight (90%), upright plant score (86%), first pod insertion height (85%), shattering (83%), plant height (76%), days to physiological maturity (70%), lodging (62%), stem diameter (60%), number of pods per plant (50%) and yield (41%) would be fairly easy to select because they show a smaller effect of environment on their expression, respectively, while the number of branches per plant (29%) would be practically difficult to select for, because it is highly masked by the environment. The heritability values are similar to those estimated by Oliveira et al. (2015). A breeder could improve the seed weight, upright plant score (upright architecture as a whole), first pod insertion height, shattering, plant height, days to physiological maturity, lodging and stem diameter using phenotype dependant selection methods such as mass selection or by hybridisation. This is because high values of broad sense heritability indicate the importance of genetic variance in the inheritance of the trait. Therefore, selection that highly depend on phenotyping would increase the frequency of favourable alleles in the population within a short period of time. On the other hand, pods per plant, yield and number of branches per plant could be effectively improved through progeny testing and family selections.

The expected genetic gain from selection is another vital parameter in evaluating the genetic potential of a population. It is said to be low when it is less than 10%, medium when between 10 and 20% and high when above 20% (Hamdi et al., 2003). All traits evaluated in this study showed a high expected genetic gain, except for the number of branches per plant, which had a low value of 15.9%. High genetic gains were recorded for lodging (116.3%), shattering (96%) and the upright plant score (64.1%), indicating a precise prediction of gain from selection (Roquib and Patnaik, 1990). However, the genetic gains for the upright plant architecture, seed yield and hundred seed weight were similar to what was reported by Pereira et al. (2008). Therefore, reliable genetic gains can be achieved within a round of selection at 5% selection intensity for the seed weight, upright plant score, first pod insertion height, shattering, plant height, days to physiological maturity, lodging and stem diameter, because they have a high expected genetic gain as well as high heritability.

4.7 Conclusion

High genetic variability was observed in the population on days to physiological maturity, lodging, plant height, number of pods per plant, seed weight and first pod insertion height. On the other hand, moderate variability was observed on stem diameter, upright plant score, yield and shattering. Moderate to high heritability values were observed across all traits except for number of branches per plant which recorded a low value. The expected genetic gain from selection was high in all traits, except for the number of branches per plant, which showed a low expected genetic gain. Generally the study showed an opportunity of selecting for the upright bean architecture from the available genotypes. These traits can be improved through hybridisation and family selection in future breeding programmes.

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Chapter 5

Evaluation of architectural traits related to direct harvesting for South African genotypes

Abstract

Evaluation of genetic diversity among crop germplasm allows breeders to exploit superior genotypes to develop new improved cultivars. The objective of this study was to evaluate selected South African genotypes for morphological/architectural traits related to direct harvesting. Twenty-four genotypes from the National Cultivar Evaluation Trial, which are a collection from various seed companies in South Africa were planted at Ukulinga Research Farm in the 2016/17 growing season. The trial was laid out in a 6 × 4 alpha lattice design with three replications. Data were collected on days to physiological maturity, days to 50% flowering, plant height, stem diameter, first pod insertion height, lodging, shattering, number of branches per plant, upright plant score, number of pods per plant, seed weight and seed yield. The analysis of variance showed highly significant differences ($p \leq 0.001$) on the days to physiological maturity, days to 50% flowering, plant height, lodging, number of branches per plant, upright plant score, number of pods per plant and seed weight. Very significant differences ($p \leq 0.05$) were observed for the first pod insertion height, stem diameter, shattering and seed yield. Superior genotypes were identified using the grand means of the different traits and these genotypes may be used in a breeding programme to improve the suitability to direct harvesting. The correlation analysis showed that plant height would be useful indirect selection of the first pod insertion height, lodging and seed weight. However an optimum height, which can reduce lodging and improve the upright architecture of the plant, should be selected for. The factor analysis revealed that seed yield, upright plant score, first pod insertion height, plant height and lodging had much influence on the variation in the data set and as such may be considered during selection.

Key words: Architectural traits, direct harvesting, dry bean, South African genotypes

5.1 Introduction

Dry bean (*Phaseolus vulgaris L.*) is the second most important legume in the world after soybean, and is the most important in terms of direct human consumption (Broughton et al., 2003). It is produced in a wide range of environments and in different cropping systems across the world. As of 2015, world production was estimated at 21.7 million tons (Nedumaran et al., 2015), with Latin America leading in terms of production and consumption. Dry bean is an important crop in Africa, grown for its rich nutrition. It is an important source of proteins, folic acid, dietary fibre, complex carbohydrates, iron and zinc (Beebe, 2003). East Africa, is the major producer and consumer of dry bean in Africa (Jones, 1999). The crop is grown traditionally as a subsistence crop across sub-Sahara Africa, mainly by women, though an economic survey by the East African Bean research Network (EABRN) shows that producers sell approximately 50% of their produce to urban markets (CIAT, 2000).

Although dry bean is mainly grown as a subsistence crop by small-holder farmers in Sub-Saharan Africa (FAO, 2017), in South Africa it is primarily grown for the market by commercial producers on large acreages across the country (Liebenberg et al., 2002). Such producers always seek to maximise profits by improving yields and quality of the crop. One field operation with a direct bearing on dry bean profitability is harvesting (Thomas et al., 2016). Harvesting establishes the return on yield and quality. The windrow system followed by threshing method is expensive on big acreages, hence the recent interest by South African commercial dry bean producers in direct combine harvesting (Joubert, 2011). Direct harvesting has the advantages of assured grain quality, and the saving of time and labour (Harrigan et al., 1992).

While direct harvesting is a new practice in South Africa (Joubert, 2011), it has been used in the United States for over 40 years (Thomas et al., 2016) on navy beans and pinto cultivars. This practice was made possible through breeding advances towards an upright bean architecture suitable for direct harvesting. The breeding of upright architecture for direct harvesting in dry bean started in the early 1940s at Michigan State University (Kelly, 2001). Ten years later, a determinate upright Type I bush bean cultivar called Sanilac was developed through mutagenesis and was later used as a parent in upright architecture breeding programmes (Down and Anderson, 1956). In the early 1970s, the ideotype breeding approach (Donald, 1968) was adopted in the development of upright dry bean cultivars. Through this breeding approach, the use of diverse bean genotypes to define a bean ideotype was suggested (Adams, 1973). An ideotype of dry bean cultivar suitable for direct harvesting was later defined as one with three to four upright basal branches, a thick hypocotyl, narrow plant profile, a height of 50 to 55 cm and high yielding (Adams, 1982). Although it was easy to convert navy and black beans into upright plant architecture, it was very challenging for pinto cultivars (Kelly and Adams, 1987). It involved the use of recurrent selection to transfer the upright architecture trait from the navy and black beans into pinto and great north cultivars. These efforts resulted in pinto cultivars with an architecture suitable for direct harvesting. However, the yield was pretty low compared to the original Type III cultivars (Kelly et al., 1990). By mid to late 2000s, a second generation of pinto cultivars was developed, which combined the upright architecture suitable for direct harvesting and with competitive yields, such as the cultivars Lariat and Stampede (Singh et al., 2007).

The objective of this study was to evaluate South African genotypes from the 2016/2017 National Cultivar Evaluation Trial for architectural traits related to direct harvesting in dry bean. The information generated will be useful in developing a breeding programme for upright dry bean cultivars to be used for direct harvesting in South Africa.

5.2 Materials and methods

5.2.1 Plant materials

The materials evaluated were 24 diverse genotypes from the 2016/2017 National Cultivar Evaluation Trial of the Agriculture Research Council in collaboration with Seed Companies and the Department of Agriculture. They included bean with both Type I and II growth habits. The genotypes came from different seed companies in South Africa. The list of genotypes is presented in Table 5.1.

Table 5.1 List of dry bean National Cultivar Evaluation Trial entries, 2016/17 season evaluated in the current study.

No.	Cultivar	Growth habit	no.	Cultivar	Growth habit
1	RUBY	II	13	OPS-RS 4	II
2	DBS 310	II	14	DBS 840	II
3	KRANSKOP	II	15	RS 5	I
4	TYGERBERG	II	16	RS 7	II
5	ORIBI	I	17	SEDERBERG	II
6	DBS 830	II	18	DBS 360	II
7	PAN 9216	II	19	WERNA	II
8	KRANSKOP-HR1	II	20	PAN 9292	II
9	TEEBUS-RR1	I	21	PAN 9141	I
10	SW 1	I	22	PAN 148	II
11	CALEDON	I	23	RS 6	II
12	PAN 123	I	24	KAMIESBERG	II

5.2.2 Experimental site

The genotypes were evaluated in the 2016 / 2017 growing season at Ukulinga Research Farm, located in KwaZulu-Natal province of South Africa (26^{0}70$^{''}$S and 27^{0}10$^{''}$E). Ukulinga is located at an altitude of 775 meters above sea level. The site has a clay soil texture (Jarvie and Shanahan, 2008) and receives seasonal rainfall from October to May, and the weather data for the study period is presented in Table 5.2.

Table 5.2 2016 / 17 rainfall and temperature data for Ukulinga research farm during the study period.

Month	Min Temp (^{0}C)	Max Temp (^{0}C)	Rainfall (mm)
November	14.7	23.0	76.0
December	13.7	38.5	33.0
January	11.6	37.9	70.0
February	14.5	36.6	94.0
March	11.7	37.2	32.3
April	7.8	36.4	36.6
May	7.2	30.8	56.9
June	6.0	28.0	1.0
Average	10.9	33.8	53.8
Total			453.5

Min temp- minimum temperature, Max temp- maximum temperature,

5.2.3 Experimental design

Genotypes were planted in a 6 × 4 alpha lattice design with three replications. A plot consisted of four rows of 5 m length with an inter-row and intra-row spacing of 0.75 m and 0.075 m, respectively.

5.2.4 Experimental management

The trial area was disked and harrowed prior to planting to attain a fine tilth. Planting was done on 28 February, 2017. One seed was planted per hill manually. A pre-emergent herbicide was sprayed after planting to control grasses and broad-leafed weeds. Supplementary irrigation was provided using sprinklers during dry spells. Routine hand weeding was carried out at two weeks and six weeks after planting. Fertilizer application was done according to local recommendations (Department of Agriculture, 2011)

5.3 Data collection

Data were collected on 12 traits namely plant height, stem diameter, upright plant score, days to 50% flowering, days to physiological maturity, number of branches, first pod insertion height, lodging, shattering, number of pods per plant, seed weight and seed yield as described in Table 5.3. All traits were obtained from a sample of 10 plants per plot, except for days to physiological maturity, seed weight, upright plant score and seed yield, which were collected on per plot basis.

Table 5.3 List of traits collected in the study

Trait	Code	Measurement
Upright plant score	UPS	Determined by assigning rating of 1-5, as outlined by Collicchio et al. (1997). Where 1= an upright single stem with high pod clearance from the soil surface, 2 = an upright plant with some ramification and high pod clearance, 3 = an upright plant with some ramification and low pod clearance, 4 = an upright plant with many ramifications and tendency to prostrate and 5 = a plant with long internodes and very prostrate
Plant height	PH	Length of central axis including vine, measured in cm at maturity.
Stem diameter	SD	Stem diameter above soil surface in mm, measured at maturity using a Vernier callipers
First pod insertion height	FPIH	Measured in cm from soil surface to first pod insertion at maturity.
Lodging	LDG	Observed and recorded by assigning ratings (1-9) at harvesting maturity, of which score 1 = upright and 9 = most prostrate.
Shattering	SHT	Observed and recorded as either shattering (score 2) and non-shattering (score 1) at harvesting maturity
Number of branches per plant	NB	Determined by counting the number of basal branches at maturity
Days to 50% flowering	F-50%	Determined as number of days from the planting date to the date when 50% of the plants had flowered.
Days to physiological maturity	DPM	Determined as number of days from the planting date to the date when 80% of the pods and leaves had dried.
Number of pods per plant	PPP	Determined by counting the total number of pods in the whole plant at maturity
Seed weight	SW	Determined by counting and weighing hundred seeds in grams
Seed yield	Y	Determined as the weight of all seeds per plot at harvesting in t ha^{-1}

5.4 Data analysis

All the measured traits were subjected to analyses of variance using Genstat statistical software 18th edition (Payne, 2014). The morphological traits of genotypes in the data set were compared using the least significant differences at 5% level and the coefficients of variation (CV %) were calculated. Pearson's correlations analysis was performed to determine the relationships among variable traits. Further, principal component and cluster analyses were performed.

5.5 Results

5.5.1 Analysis of variance of traits

The analysis of variance showed highly significant differences ($p \leq 0.001$) in the number of days to physiological maturity, days to 50% flowering, lodging, number of branches per plant, plant height, number of pods per plant, seed weight and the upright plant score Table 5.4. Moderately significant differences ($p \leq 0.01$) were observed on first pod insertion height. The stem diameter, shattering and seed yield were significant at the 0.05 level.

Table 5.4 Anova table for twelve traits studied

Source of variation	DF	DPM	FPIH	F 50%	SD	LDG	NB	PH	PPP	SHT	SW	UPS	Y t/ha
Replication	2	29.29ns	13.30*	0.68ns	0.09ns	16.10***	0.12ns	58.28ns	11.95ns	0.01ns	2.63ns	0.00^{00}ns	0.07ns
Incomplete blocks	12	16.84ns	14.42***	11.91***	0.72**	4.27***	0.43ns	125.08ns	39.5***	0.12ns	146.39***	1.94^{-01}***	0.15ns
Genotype	23	36.27***	7.75**	18.04***	0.56*	4.38***	0.75***	405.09***	46.42***	0.20*	446.81***	5.46^{-01}***	0.19*
Residual	34	9.80	3.28	0.3454	0.29	1.35	0.27	64.29	10.81	0.10	8.043	1.50^{-16}	0.09
Total	71	20.11	6.90	8.0421	0.45	3.24	0.45	184.8	27.23	0.13	173.41	2.10^{-01}	0.13

DF- degrees of freedom, DPM-days to maturity, SD-stem diameter, LDG-lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB-number of branches per plant, FPIH-first pod insertion height and SHT-shattering

5.5.2 Mean performance of local cultivars for the twelve traits

The results showed that the mean days to flowering was 47 days and the range among genotypes was from 42 in PAN 9141 to 52 days in Ruby. The average days to maturity was 103.2 days, of which RS 5 was the earliest to mature with 96.7 days, while Werna was the latest with 109.3 days. The first pod insertion height was diverse, with a mean of 13.7 cm. Genotypes Oribi, RS 5, DBS 310, DBS 360, DBS 840, Kamiesberg, Kranskop-HR1, OPS-RS 4, PAN 148, Ruby, Sederberg and Werna, had their first pod insertion heights above the mean. The first pod insertion height ranged from 10.3 cm in Caledon to 18 cm in DBS 360. The average stem diameter of 6.70 mm was recorded, with Teebus-RR1 having the thinnest stems of 5.9 mm, while SW 1 recorded the thickest stems of 7.8 mm. However, seven genotypes recorded diameters thicker than the data set mean and these were RS 7, DBS 830, Oribi, DBS 840, Sederberg, Caledon and SW 1. The mean lodging score was 3.1. Genotype Werna recorded the highest lodging score of 6, while the genotypes Teebus-RR1 and PAN 123 recorded the lowest lodging score of 1.3. Fifteen Genotypes namely Caledon, Oribi, PAN 123, PAN 9141, RS 5, SW 1, Teebus-RR1, DBS 310, Kamiesberg, Kraskop-HR1, OPS-RS 4, PAN 148, PAN 9216, PAN 9292 and Tygerberg recorded a lodging score lower than the mean. The number of branches per plant ranged from 2.6 in cultivar PAN 9216 to 4.7 in PAN 9141, while the population average was 3.5. The tallest plants were recorded in the cultivar DBS 830 with a height of 73.3 cm and the shortest plants were in Oribi with a height of 37.1 cm. The mean plant height for the data set was 59.7 cm. The number of pods per plant ranged from 9.3 in PAN 9216 to 25.8 in Caledon and the population mean was 13.4. Four genotypes that included Caledon, PAN 123, PAN 9141 and SW 1 recorded higher number of pods per plant than the mean. The data set mean for shattering was 1.2 and 16 genotypes namely Caledon, Oribi, PAN 123, SW 1, Teebus-RR1, DBS 310, DBS 830, DBS 840, Kamiesberg, Kranskop, Kranskop-HR1, OPS-RS 4, PAN 148, RS 7, Ruby and Werna recorded a score lower than the mean. The average seed size was 48.5 g per hundred seeds, of which SW 1 seeds were the smallest, weighing 20 g, while seeds for the cultivar Oribi were the largest, weighing 69.9 g. The mean upright architecture score recorded for the data set was 3.7 and seven cultivars namely SW 1, Caledon, PAN 123, PAN 9141, Teebus-RR1, RS 5 and Oribi recorded an upright architecture score below the mean. The average seed yield recorded was 1.9 t ha^{-1}. The cultivar SW 1 was the lowest yielding with 1.2 t ha^{-1}, while the cultivar Kamiesberg was the highest with 2.5 t ha $^{-1}$. However, nine cultivars yielded above the mean namely Kamiesberg, Sederberg, PAN 9292, Werna, Teebus-RR1, RS 6, Oribi, Tygerberg and RS 7 (Table 5.5).

Table 5.5 Trait means of local genotypes from the 2016/17 national cultivar trial listed from most upright to the most prostrate

GENOTYPE	DPM	FPIH	F 50%	SD	LDG	NB	PH	PPP	SHT	SW	UPS	Y t/ha
CALEDON	105.0	10.3	49.0	7.6	2.7	4.1	50.9	25.8	1.0	21.7	3.0	1.8
ORIBI	105.0	14.1	48.0	7.0	1.7	2.9	37.1	9.5	1.0	69.9	3.0	2.2
PAN 123	101.0	12.1	44.0	6.7	1.3	4.0	41.5	15.7	1.0	28.0	3.0	1.8
PAN 9141	104.0	11.4	42.0	6.1	1.4	4.7	39.8	20.3	1.3	30.9	3.0	1.8
RS 5	97.0	15.8	42.0	6.7	2.0	2.9	46.6	11.1	1.7	57.0	3.0	1.8
SW 1	107.0	11.8	50.0	7.8	1.7	4.3	46.2	22.9	1.0	20.0	3.0	1.2
TEEBUS-RR1	100.0	11.1	42.0	5.9	1.3	4.3	40.7	20.2	1.0	33.3	3.0	2.1
DBS 310	101.0	14.2	50.0	6.7	2.3	3.4	64.8	13.4	1.0	54.0	4.0	1.8
DBS 360	97.0	18.0	45.0	6.3	5.9	3.3	62.3	12.1	1.7	45.3	4.0	1.9
DBS 830	109.0	13.7	47.0	6.9	3.7	3.5	73.3	12.3	1.0	52.7	4.0	1.7
DBS 840	101.0	15.9	48.0	7.3	4.7	3.2	70.0	10.7	1.0	51.0	4.0	1.9
KAMIESBERG	106.0	14.5	50.0	6.7	2.0	3.2	56.2	11.4	1.0	61.0	4.0	2.5
KRANSKOP	99.0	12.7	50.0	6.7	3.2	3.4	66.0	12.3	1.0	52.6	4.0	1.9
KRANSKOP-HR1	101.0	14.3	47.0	6.3	3.0	3.6	71.6	12.7	1.0	52.2	4.0	1.7
OPS-RS 4	108.0	17.5	47.0	6.7	2.3	3.5	70.7	12.1	1.0	51.7	4.0	1.9
PAN 148	101.0	13.8	50.0	6.1	2.7	3.5	61.1	11.0	1.0	49.3	4.0	1.9
PAN 9216	102.0	11.7	47.0	6.6	2.2	2.6	62.6	9.3	1.7	58.9	4.0	1.8
PAN 9292	108.0	12.6	49.0	6.7	2.3	3.1	56.7	11.5	1.3	50.0	4.0	2.1
RS 6	102.0	13.3	47.0	6.1	4.6	3.6	65.2	12.2	1.4	51.9	4.0	2.2
RS 7	103.0	12.3	45.0	6.8	4.0	3.6	70.3	9.6	1.0	54.0	4.0	2.4
RUBY	101.0	14.0	52.0	6.6	4.7	3.0	68.1	12.1	1.0	37.7	4.0	1.8
SEDERBERG	104.0	15.2	48.0	7.4	4.7	3.9	70.8	11.8	1.3	57.0	4.0	2.0
TYGERBERG	105.0	13.4	50.0	6.5	2.7	3.5	67.9	10.8	1.4	63.9	4.0	2.2
WERNA	109.0	15.0	45.0	6.7	6.0	3.6	69.3	10.8	1.0	59.3	4.0	2.1
Grand mean	103.0	13.7	47.0	6.7	3.1	3.5	59.7	13.4	1.2	48.5	3.7	1.9

GENOTYPE	DPM	FPIH	F 50%	SD	LDG	NB	PH	PPP	SHT	SW	UPS	Y t/ha
SE	3.13	1.81	0.59	0.54	1.16	0.52	8.02	3.29	0.31	2.84	0	0.29
LSD (5%)	5.20	3.01	0.98	0.89	1.93	0.86	13.33	5.47	0.52	4.72	0	0.49
CV (%)	3.03	13.18	1.24	8.04	37.96	14.63	13.44	24.54	27.29	5.85	0	15.18

DF-degrees of freedom, DPM-days to maturity, SD-stem diameter, LDG-lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB-number of branches per plant, FPIH-first pod insertion height and SHT-shattering

5.5.3 Correlations

Table 5.6 presents the correlation coefficients of twelve traits studied, describing the levels of association between each pair. Significant correlation were observed on the first pod insertion height with lodging (r = 0.50), the number of branches per plant (r = -0.44), plant height (r = 0.43), the number of pods per plant (r = -0.57), seed weight (r = 0.49) and upright plant score (r = 0.44). The days to 50% flowering was positively correlated to upright plant architecture score (r = 0.45). Lodging showed high significant positive correlation with plant height (r = 0.69) and upright architecture score (r = 0.62). The number of branches per plant was positive and significantly correlated with the number of pods per plant (r = 0.77), however, it was negative and significantly correlated with seed weight (r = -0.69) and the upright plant score (r = -0.46). The plant height was negatively correlated with the number of pods per plant (r = -0.53), but positively correlated to seed weight (r = 0.43) and upright architecture score (r = 0.91). The number of pods per plant showed a negative significant correlation with seed weight (r = -0.88), upright plant architecture score (r = -0.68) and seed yield (r = -0.44). The seed weight was positively and significantly correlated with the upright plant architecture score (r = 0.56) and seed yield (r = 0.56).

Table 5.6 Pearsons' correlation coefficients among the twelve traits

Trait	DPM	FPIH	F 50%	HD	LDG	NB	PH	PPP	SHT	SW	UPS	Y
DPM	1											
FPIH	-0.15	1										
F 50%	0.23	0.01	1									
HD	0.34	-0.04	0.37	1								
LDG	-0.06	0.50*	0.11	0.04	1							
NB	0.15	-0.44*	-0.34	-0.02	-0.20	1						
PH	0.11	0.43*	0.39	0.02	0.69**	-0.32	1					
PPP	0.10	-0.57**	-0.13	0.23	-0.38	0.77**	-0.53**	1				
SHT	-0.34	0.19	-0.32	-0.21	0.10	-0.27	-0.05	-0.22	1			
SW	0.05	0.49*	0.13	-0.16	0.24	-0.69**	0.43*	-0.88**	0.20	1		
UPS	0.09	0.44*	0.45*	-0.17	0.62**	-0.46*	0.91**	-0.68**	0.03	0.56**	1	
Y	0.07	0.08	-0.06	-0.32	0.12	-0.23	0.06	-0.44*	0.01	0.56**	0.25	1

**Correlation is significant at the 0.01 level, *correlation is significant at the 0.05 level (2-tailed). DPM- days to maturity, SD-stem diameter, LDG-lodging, PH- plant height, PPP- number of pods per plant, SW- seed weight, UPS- upright plant score, Y- seed yield, NB- number of branches per plant, FPIH- first pod insertion height and SHT- shattering

5.5.4 Principal component analysis

The genetic variation of the 24 genotypes attributed to by the twelve traits related to direct harvesting were measured through a principal component analysis. Four eigenvalues greater than one were obtained indicating that four principal components were important in the study. The four principal components cumulatively explained a total variation of 76.69%. The first principal component (PC-1) had an eigenvalue of 4.53 and accounted for 37.76% of total variation, and this was mainly contributed to by seed weight, seed yield, the upright architecture score, first pod insertion height and the days to 50% flowering. The second principal component recorded an eigenvalue of 2.14 accounting for 17.79% of the total variation contributed mainly by plant height and lodging. The number of branches per plant, the days to physiological maturity and the stem diameter are the traits that contributed most to the 11.52% of the total variation with an eigenvalue of 1.38 observed in the third principal component (PC-3). The principal component four had an eigenvalue of 1.16 explaining only 9.62% of the total variation mainly attributed to the number of pods per plant and shattering (Table 5.7).

Table 5.7 Principal component analysis of twelve traits showing the explained variance, proportion of total variance and the cumulative variance.

Trait	PC-1	PC-2	PC-3	PC-4
SW	0.88	0.25	0.02	-0.20
NB	-0.87	-0.15	0.21	-0.24
PPP	-0.83	-0.41	0.13	0.17
PH	0.23	0.90	0.17	0.08
LDG	0.03	0.87	-0.10	-0.02
UPS	0.43	0.82	0.17	-0.06
FPIH	0.38	0.55	-0.35	0.06
DPM	0.02	-0.01	0.76	0.11
SHT	0.22	-0.01	-0.74	-0.09
SD	-0.05	-0.07	0.25	0.80
Y	0.53	-0.01	0.27	-0.65
F 50%	0.29	0.24	0.48	0.57
Explained variance (eigenvalue)	4.53	2.14	1.38	1.16
Proportion of total variance (%)	37.76	17.79	11.52	9.62
Cumulative variance (%)	37.76	55.55	67.07	76.69

PC-1- principal component 1, PC-2- principal component 2, PC-3- principal component 3,PC-4-principal component 4, DPM-days to physiological maturity, SD-stem diameter, LDG-lodging, PH-plant height, PPP-number of pods per plant, SW-seed weight, UPS-upright plant score, Y-seed yield, NB- number of branches per plant, FPIH-first pod insertion height and SHT-shattering

5.5.5 Cluster analysis

The phenotypic means of traits were used to develop a similarity matrix for the 24 genotypes evaluated using Euclidian coefficients in Genstat Statistical Software (Payne, 2014). A dendrogram was then developed and is presented in Figure 1.4.1. Two clusters were observed namely; cluster I and III. Cluster number III had the largest number of genotypes that included Kamiesberg, Tygerberg, PAN 9292, Kranskop-HR1, DBS 310, Kranskop, PAN 148, Ruby, DBS 840, Sederberg, DBS 830, OPSR 34, Werna, RS 7, PAN 9216 and DBS 360. Cluster I had five genotypes namely; Caledon, SW 1, PAN 123, Teebus-RR1 and PAN 9141. Genotypes RS 5 and Oribi were stand alone. The most similar genotypes in this study were Kranskop and DBS 310, with a similarity percentage of 99.1. However the most distinct were SW 1 and DBS 830 with a similarity percentage of 47.2.

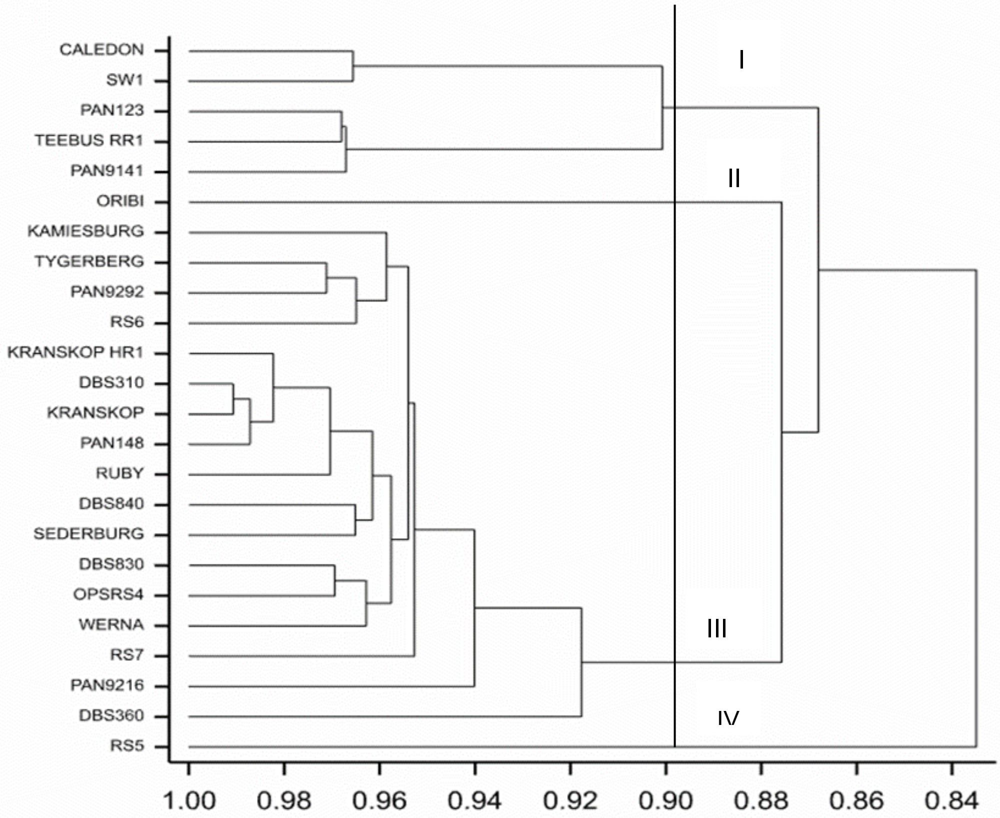

Figure 5.1 Dendrogram showing cluster analysis of 24 dry bean genotypes from the 2016/17 National Cultivar Evaluation Trial

5.6 Discussion

The highly significant differences ($p \leq 0.001$) observed on the days to physiological maturity, days to 50% flowering, lodging, number of branches per plant, plant height, number of pods per plant, seed weight and the upright plant score from the analysis of variance indicate the presence of high genetic diversity in the data set and the possibility of cultivar improvement through selection for these traits. On the other hand the moderate significant differences ($p \leq 0.05$) observed on the first pod insertion height, stem diameter, shattering and seed yield shows moderate diversity for these traits. The results on plant height, lodging, days to flowering, days to maturity and seed weight are similar to what was reported by Soltani et al. (2016), who, however, also reported highly significant differences on stem diameter and seed yield. The limited diversity in stem diameter and seed yield observed in this study could be attributed to the limited growth habits of the genotypes used (Types I and II), compared to a wide range of growth habits (Types I, II, IIb and III) used by Soltani et al. (2016).

Days to physiological maturity is an important trait that is used to determine the earliness or lateness of a cultivar, however the ultimate selection criteria for combine harvesting is uniformity in maturity. Variations would lead to losses because the combine cannot thresh immature pods. The mean days to maturity recorded in the data set was 103 days. Kelly (2001), stated that an early cultivar with long periods between flowering and maturity, is preferred for combine harvesting. A number of cultivars that included PAN 123, RS 5, Teebus-RR1, DBS 310, DBS 360, DBS 840, Kranskop, Kranskop-HR1, PAN 148, PAN 9216, RS 6 and Ruby matured earlier than the mean for the data set and could be considered for selection for earliness. The first pods insertion height translates into raised pods in breeding for combine harvesting and this is important to avoid combine header losses and sclerotinia (Moura et al., 2013). The first pod insertion height ranged from 10.3 to 18 cm with a mean of 13.7 cm. The higher the first pod insertion height, the easier it becomes for the header to pick up the pods. Twelve genotypes had their first pod insertion heights higher than the mean and would be considered for selection to improve the trait. The genotypes included Oribi, RS 5, DBS 310, DBS 360, DBS 840, Kamiesberg, Kranskop-HR1, OPS-RS 4, PAN 148, Ruby, Sederberg and Werna. The stem diameter recorded in the data set was 6.7 mm, a value slightly higher than what was reported by Soltani et al. (2016). Kelly (2001), reported that a sturdy stem diameter is important in breeding for combine harvesting for strong stems to avoid lodging. Therefore, selections for sturdy stem diameters would include cultivars RS 7, DBS 830, Oribi, DBS 840, Sederberg, Caledon and SW 1. However, there is a need to define an optimum stem diameter that greatly minimises lodging coupled with higher yields and sufficient clearance. On the other hand, lodging and shattering are traits that will be selected against when breeding for combine harvesting, in order to reduce harvest losses. Lodging scores in the data set ranged from 1.3 to 6 with a mean of 3.1. The genotypes with a score lower than the population mean would preferably be considered for selection for resistance to lodging and these included Caledon, Oribi, PAN 123, PAN 9141, RS 5, SW 1, Teebus-RR1, DBS 310, Kamiesberg, Kranskop-HR1, OPS-RS 4, PAN 148, PAN 9216, PAN 9292 and Tygerberg. Those that were non-shattering were Caledon, Oribi PAN 123, PAN 9141, SW 1, Teebus-RR1, DBS 310, DBS 830, DBS 840, Kamiesberg, Kranskop, Kranskop-HR1, OPS-RS 4, PAN 148, RS 7, Ruby and Werna. The plant height ranged from 37.1-73.3 cm with a mean of 59.7 cm which was similar to the mean of 57.7 cm reported by Soltani et al. (2016). Acquaah et al. (1991) defined an ideal plant height for combine harvesting as one with a height ranging from 50 to 60 cm.

The upright plant architecture score had a mean of 3.7 and genotypes Caledon, Oribi, PAN 9141, RS 5, SW 1 and Teebus recorded a desired score lower than the mean. However, genotype RS 5 was found to be shattering despite having an ideal architecture. Even if the upright architecture is the trait of interest when breeding for combine harvesting, seed yield remains vital. The seed yield in the data set ranged from 1.2 to 2.5 t ha^{-1}, with a mean of 1.93t ha^{-1}. Cultivars that included Kamiesberg; Sederberg, PAN 9292, Werna, Teebus-RR1, RS 6, Oribi, Tygerberg and RS 7 performed above the mean and would be considered for selection to improve yield.

Important positive and negative correlations amongst traits in relation to the improvement of dry bean architecture for direct harvesting were observed in the data set. The first pod insertion height showed positive significant correlation with plant height, lodging and the upright plant score. Moura et al. (2013), also reported a positive association between the first pod insertion height, lodging and plant height. Nevertheless, the first pod insertion height is linked to lodging, a trait not desired in the improvement of dry bean for direct harvesting. Therefore there is need to ascertain the high first pod insertion height that would give a desirable architecture for direct harvesting and minimise lodging in order for the genotype to be useful in selection. However, selecting for the first pod insertion height would result in little branches (a trait important for the plant architecture related to direct harvesting), and low number of pods on a plant, but with large grains. According to Soltani et al. (2016), an optimum plant height that would give a suitable architecture for combine harvesting needs to be critically considered, because height is positively correlated with lodging, a trait that is not desirable in dry bean for combine harvesting.

A factor analysis is an important tool in plant breeding studies to determine traits that are influential in defining variations in a given data set (Cirilo et al., 2009). This variation attributed to the influence of traits is quantified using Eigenvalues (Greenacre, 2010). The principal component analysis in this study showed that seed weight, seed yield, upright plant score, first pod insertion height and the days to 50% flowering had a high positive loading in the first principal component, explaining 37.76% of the total variation observed. This shows their influence in differentiating genotypes in the data set, and as such, they should be given first priority during selection. These traits can be selected for together. The second set of traits to be considered for selection are plant height and lodging. These two had a high loading in the second principal component, which explained a substantial amount of the total variation (17.79%). The third consideration, though with a smaller influence, would be the stem diameter, days to physiological maturity and the number of branches per plant loaded in the third component (11.52%).

The cluster analyses was used to determine how closely related the genotypes were based on traits of interest. Genotypes clustered together may be considered to be phenotypically similar or identical. The genotypes were grouped into two clusters. The largest cluster included genotypes Kamiesberg, Tygerberg, PAN 9292, Kranskop-HR1, DBS 310, Kranskop, PAN 148, Ruby, DBS 840, Sederberg, DBS 830, OPS-RS 34, Werna, RS 7, PAN 9216 and DBS 360. The other cluster had genotypes Caledon, SW 1, PAN 123, Teebus-RR1 and PAN 9141. The genotypes RSS5 and Oribi were stand alone and distant from the other clusters. Selecting distantly related genotypes for hybridization based on traits of interest, is vital to a breeder as it results in vigorous off-springs and assures favourable results. The most closely related genotypes in the data set were Kranskop and DBS 310, while the most distant ones were SW 1 and DBS 830.

5.7 Conclusion

The study identified superior genotypes based on the grand means of the traits recorded. The superior genotypes may be used in a breeding program to improve the new genotypes for suitability to combine harvesting. Seed yield, upright plant score, first pod insertion height, plant height and lodging were identified the most important traits that may be considered during selection when improving the suitability for combine harvesting. Plant height was found to be an important trait to be used for multiple selection due to its association with lodging, upright plant score and the first pod insertion height. However, an optimum height that would minimise lodging and improve the upright architecture may need to be defined.

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Chapter 6

Summary and recommendations

6.1 Introduction

Dry bean is one of the most important field crops in South Africa. It is grown for its high protein content, dietary benefits and its importance as a source of income to growers. The crop is predominantly grown by commercial producers for the market, with the leading provinces being Mpumalanga, Gauteng, Northwest, Free State, Limpopo, KwaZulu-Natal and the Eastern Cape. The crop is mainly grown by small scale farmers. The manual or mechanical pulling of the beans into windrows followed by is a labour intensive and costly system on large acreages. Commercial producers have sought the use of the direct harvesting system using combine, which is cost effective on large acreages. However, the implementation of the direct harvesting system requires a suitable cultivar with an upright plant architecture, competitive yields and a good pod clearance from the ground. Therefore, it is important to evaluate both local and international germplasm for traits related to direct harvesting. This chapter outlines the findings on the pre-breeding study of architectural traits related to direct harvesting in dry bean.

The specific objectives of the study were:

To evaluate architectural traits related to direct harvesting and establish trait relationships on selected genotypes from the Andean genepool.

To estimate the phenotypic and genotypic variation, heritability, and genetic gain for morphological traits related to direct harvesting.

To evaluate architectural traits related to direct harvesting and establish trait relationships on selected South African genotypes.

6.2 Summary of the research findings

6.2.1 Evaluation of architectural traits related to direct harvesting for selected genotypes from the Andean gene pool.

The analysis of variance revealed a large genetic variation on all traits, except for the number of branches per plant, which had a moderate variation. Genotype by site interaction was observed on the days to physiological maturity, lodging, plant height and seed weight. The traits greatly varied, the upright plant score ranged from 2 to 4 with a mean of 2.8, days to physiological maturity varied from 64.2 to 90.3 days with a mean of 76.6 days, stem diameter varied from 5.7 to 8.3 mm with a mean of 6.9 mm, lodging varied from 1.7 to 8.3 with a mean of 3.4, plant height varied from 42.2 to 79.4 cm with a mean of 53.4 cm, the number of branches per plant varied from 2.8 to 4.4 with a mean of 3.8, the number of pods per plant varied from 7.9 to 16.1 with a mean of 11.7, seed weigh varied from 38.4 to 61.1 g with a mean of 51.5 g and seed yield varied from 1.1 to 1.9 t ha^{-1} with a mean of 1.5 t ha^{-1}. Seven genotypes were found to be non-shattering. Superior genotypes for each trait, were identified based on the mean. The stem diameter showed an important positive significant correlations to the days to physiological maturity, seed yield and number of branches per plant, and a negative significant correlation to lodging and upright plant score. The principal component analysis resulted into three components explaining 78.55% of the variation, which were mainly contributed to by the days to physiological maturity, seed yield, stem diameter, plant height and number of branches per plant.

6.2.2 Estimation of the phenotypic and genotypic variability, heritability, and genetic gain of traits related to direct harvesting in dry bean

The study observed high genotypic and phenotypic coefficients of variation for all traits, except for the days to physiological maturity, stem diameter and the number of branches per plant where the variations were moderate. Moderate to high heritability estimates were observed, except for the number of branches per plant, where a low value was recorded (29%). The genetic advance as a percentage of the mean (genetic gain) was high for all traits.

6.2.3 Evaluation of architectural traits related to direct harvesting for South African genotypes

The analysis of variance showed highly significant differences for the number of days to physiological maturity, days to 50% flowering, lodging, number of branches per plant, plant height, number of pods per plant, seed weight and the upright plant score. It was very significant for the first pod insertion height and moderate for stem diameter, shattering and seed yield.

The days to 50% flowering had a mean of 47 and ranged from 42 to 52 days, the mean days to maturity was 103.2 days with a range of 96.7 to 109.3 days, while the mean first pod insertion height was 13.7 cm with a range of 10.3 to 18 cm. The mean stem diameter was 6.70 mm and ranged from 5.9 mm to 7.8 mm, mean lodging score was 3.1 and ranged from 1.3 to 6, mean number of branches per plant was 3.5 with a range from 2.6 to 4.7, plant height ranged from 37.1 to 73.3 cm with a mean of 59.7 cm, number of pods per plant ranged from 9.3 to 25.8 with a mean of 13.4, sixteen genotypes were found to be non-shattering, seed size ranged from 20.0 to 69.9 g with a mean of 48.5 g, upright plant architecture score recorded a mean of 3.7, and seven cultivars had a desirable score below the mean, and the seed yield ranged from 1.2 t ha^{-1} to 2.5 t ha^{-1} with a mean of 1.9 t ha^{-1}. The plant height was found to be positively and significantly correlated with the first pod insertion height, lodging, seed weight and upright plant score, and was negatively correlated to the number of pods per plant. The factor analysis revealed four significant principal components accounting to 76.69% of variation, with the traits seed weight, seed yield, upright plant score, first pod insertion height, days to 50% flowering, plant height and lodging being main contributors. The cluster analysis separated genotypes into two main clusters with KRANSKOP and DBS 310 being the most similar while SW 1 and DBS 830 were the most distinct.

6.3 Breeding implications of the research findings

6.3.1 Evaluation of architectural traits related to direct harvesting for selected genotypes from the Andean gene pool.

The wide range of genetic diversity of the traits provides an opportunity to select parental genotypes for suitability to direct harvesting from the Andean gene pool. However, selections should be done from several locations for accuracy on the days to physiological maturity, lodging, plant height and seed weight. The stem diameter was found to be important for indirect selection of traits namely; days to physiological maturity, lodging, seed yield and the upright architecture score. It was observed that, selecting for thicker stems would improve the days to physiological maturity, resistance to lodging, seed yield and the upright plant architecture score. The factor analysis showed that the days to physiological maturity, seed yield, and the number of pods per plant, stem diameter, plant height and number of branches per plant had a large contribution to the variation observed, therefore, they should be considered for selection. The genotypes ADP 35, ADP 166, ADP 211, ADP 36, ADP 395, ADP 436, ADP 455, ADP 458, ADP 661, Mbomvu and Ukulinga were found to have thicker stem and were non-shattering, and therefore, they may be considered as parents in improving the suitability to direct harvesting.

6.3.2 Estimation of the phenotypic and genotypic variability, heritability, and genetic gain of traits related to direct harvesting in dry bean

The high genotypic and phenotypic coefficients of variation shows that the traits have a high scope for selection and would show a great response. The environmental influence was minimal on the traits, indicating the easiness and reliability of selection. The traits that showed high heritability estimates would be easy to select for, and may be improved through mass selection and/hybridisation. However, the traits that showed low to medium heritability estimates, namely the number of pods per plant, seed yield and number of branches per plant, may be improved through progeny testing and family selection. Reliable genetic gains may be achieved in this data set, within a round of selection, at 5% intensity on the seed weight, upright plant score, first pod insertion height, shattering, plant height, days to physiological maturity, lodging and stem diameter.

6.3.3 Evaluation of architectural traits related to direct harvesting for South African genotypes

The genotypes were very diverse, signifying the possibility of selection. The plant height could be used for indirect selection for pod clearance, resistance to lodging and seed size, however, an optimum plant height needs to be defined. For the rest of the traits, direct selection should be practiced. The traits with a high positive loading in the first and second principal components should be considered during selection. Distinct genotypes with traits of interest can be crossed to improve the suitability to direct harvesting.

6.4 Conclusion and recommendations

The main objective of the study was to develop a breeding strategy for developing dry bean cultivar for suitability to direct harvesting. The evaluation on Andean genotypes identified stem diameter as an important trait for indirect selection of the upright plant architecture and seed yield. However, an optimum need to be defined. The days to physiological maturity, seed yield, stem diameter, plant height and number of branches per plant were important traits to be considered for selection. The traits that showed high heritability can be improved through mass selection/hybridisation, while those that showed low estimates may be improved through progeny testing. However, for the local South African genotypes, plant height was important for indirect selection of the first pod insertion height, lodging and seed weight, nevertheless direct selection should be emphasized on the rest of the traits. The traits seed weight, seed yield, upright plant score, first pod insertion height, days to 50% flowering, plant height and lodging were identified to be considered during selection. The genotypes superior in all traits can be considered for the improvement of the suitability to direct harvesting.