EVALUATION OF BAMBARA GROUNDNUT (*Vigna subterranea*) FOR YIELD STABILITY AND YIELD RELATED CHARACTERISTICS

By

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CHAPTER 1

INTRODUCTION

Bambara groundnut, *Vigna subterranea*, is a self-pollinating annual legume crop, which was formerly known as *Voandzeia subterranea* (L.) Thouars. It is an African indigenous crop that has been grown for centuries. It is used for both human and animal consumption. The crop is popular in Africa because of its resistance to drought and pests, and its ability to produce reasonable yields when grown on poor soils. The crop ranks third among the grain legume crops of Africa in terms of production and consumption after groundnut and cowpea (Sellschop, 1962; Doku & Karikari, 1970; Rachie & Silvestre, 1977; Linnemann, 1992) and it is consumed in many ways. It can either be eaten in its young stage or when it is ripe.

The crop can produce high yield levels with low input and is an ideal crop for farmers. It was found that about 98% of farmers in Swaziland regard bambara nuts as a profitable crop (Sesay *et al.,* 1999; Begemann *et al.,* 2002). According to Coudert (1984), the annual production is about 330 000 tons of which Africa produces half, with Nigeria being the major producing country. The yields are low because production and improvement of bambara nut has been neglected for many years by researchers, even though the crop is important for the small scale farmers due to its considerable commercial potential. There is also little information on production levels.

Information about the crop in South Africa is limited and only a small group of people knows the role of the crop in the society. Small-scale farmers and a limited group of people in the rural areas mainly grow the bambara groundnut as a subsistence crop. According to farmers in the Mpumalanga province (South Africa) the crop was introduced in the dry season when popular crops such as maize cannot produce better yields. It is therefore called the poor man's crop, as

it is an alternative source of food proteins for the small scale farmers and sometimes acts as a means of survival in times of drought induced famine.

Under unfavourable environmental conditions or moisture stress, the yields of bambara groundnuts are reduced. The crop has many attributes that are valuable when compared to other legumes when grown in its area of adaptation. It is adapted to poor soils that are sandy. The most important trait of the crop is its drought tolerance, which allows it to be grown where cultivation of other legumes is not viable (Vietmeyer, 1979). It is biologically better adapted to semi-arid or arid as well as marginal areas, than locally competing grain legumes. It is also capable of increasing the level of soil nitrogen because it produces its own nitrogen, thus giving acceptable grain yields where other crops usually fail. Therefore it would be of use in low-input agricultural production.

Recently, bambara groundnut has gained a renewed interest by researchers as a food crop. The crop is very important because it has the ability to conserve and increase the natural soil fertility and health, by better use of the environmentally constrained areas with its adaptability to drought, and nitrogen fixation. It can also diversify income opportunities of the farmers and the community. It is not surprising that calls have been made for governments and research stations to give more attention to the possibilities of increasing production of bambara groundnuts, since it is one of the five most important sources of protein that is mostly consumed in SADC countries (Linnemann, 1987; Azam-Ali, 1993). Up to date little or no studies have been done on the yield stability of bambara groundnut genotypes. The objectives of this study were to:

- determine yield stability of bambara groundnut genotypes
- determine the relationship between yield and related characteristics
- asses the effect of planting date on yield and yield components of the genotypes
- study the effect of location and genotype on protein quantity of the bambara groundnut.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of the bambara groundnut

Bambara groundnut is a crop that is grown mainly at subsistence level and its annual production level is estimated around 330 000 tons, of which Nigeria produces almost a third. The worldwide demand of the crop is much higher than its production (Swanevelder, 1998).

2.2 History in terms of taxonomy, origin and distribution

Bambara groundnut is believed to have originated from the African continent, especially Central Africa long before the introduction of groundnuts (peanuts). It belongs to the family Leguminosae, subfamily Papilionoideae (Goli, 1997) and is related to cowpeas. The botanical name of the crop is *Vigna subterranea* (L) Verdc, which comprises of the wild species type (*V. subterranea* var*. spontanea*) and the cultivated type (*V. subterranea* var. *subterranea*). Doku & Karikari (1971c) concluded in their study of evolution of the crop that cultivated bambara groundnut originated from *Vigna subterranea* var. *spontanea* and evolved through a series of gradual changes, including switching from open to branched growth habit, from outbreeding to inbreeding and a reduction in shell thickness. The crop has a chromosome number of 2n=22 (Heller *et al.,* 1995). The crop was named after the Bambara district on the Upper Niger near Timbuctoo (Burkill, 1906; Holm & Marloth, 1940), but the district has no claim to the plant. In the centre of origin it is cultivated from Senegal to Kenya and from the Sahara to South Africa and Madagascar (Goli, 1997).

In South Africa there is difference of opinion as to who brought bambara to the country. The people of Bolobedu claim they brought the crop when they first arrived in the south, while on the other hand the Venda people say they are the

ones who first came with it from Central Africa. The latter's case is supported by some proof; the name 'Ndluhu-mvenda', which means groundnut of Vendaland, is still used today but there is some contention, and the harvest ritual is customary for bambara groundnut. Locally it is called various names such as Phonda (Venda), Ditloo-marapo (Sepedi) and Tindhluwa (Tsonga) (Holm & Marloth, 1940), and it is cultivated in the Limpopo, Kwazulu-Natal, Mpumalanga, Eastern Cape and Northwest provinces by few smallholder farmers. Rural women mainly grow the bambara groundnut in their home gardens for consumption or as a cash crop for their own economic benefit.

2.3 Uses, consumption and economical importance of the crop worldwide

Bambara groundnut has long been used as an animal feed (Linnemann, 1991) and seeds have been successfully used to feed chicks (Oluyemi *et al.,* 1976). The leaves are suitable for animal grazing because they are rich in nitrogen and phosphorus (Rassel, 1960). The haulms were found to be palatable (Doku & Karikari, 1971) and are an important source of livestock feed during the dry season. Bambara groundnut cultivars that are resistant to foliar diseases would have a dual role of providing pods for human use and fodder for livestock feed.

The seeds are consumed in a variety of forms, either in the mature or immature state. The most common method of preparing the food is by boiling until the seeds are soft. The mature seeds are hard and have to be soaked before they can be boiled. The immature seeds are consumed fresh or grilled and they can also be boiled, either shelled or unshelled, and eaten as a meal or mixed with immature groundnut and maize. Usually they are pounded to flour and boiled to a stiff porridge, which is traditionally used for long journeys. The boiled seeds can also be pounded and then mixed with samp. In some countries like South Africa and Swaziland, bambara groundnut is used to add variety to daily diets and as a mainstay in time of starvation and it can also be used to make soup. The grains

can also be processed into a type of milk and bread (Karikari, 1971; Brough *et al.,* 1993).

Bambara groundnut has an indirect beneficial use in agriculture because it is a legume, which has a symbiotic relationship with bacteria that form root nodules. The bacteria can make use of the free nitrogen from the air and assimilate it in the plant root tissue. By so doing, they directly increase the level of the soil nitrogen, and in turn the yields of the cereal that may follow legumes in plant rotation, is increased.

2.4 Morphological characteristics of the crop

Bambara groundnut growth habit is either spreading or the bunched type. The spreading types are cross-pollinating while bunched types are self-pollinating, and the latter usually matures earlier (Goli, 1997). Morphological structure of the crop matches that of the groundnut (*Arachis hypogea*), in that it bears its fruit below the ground. The crop is a prostrate, herbaceous annual legume with a compact taproot system that is well developed, with profuse geotropic lateral roots. The taproot. Stem branching starts as early as about one week after germination and has about 20 short branches on which the leaves are borne. Each lateral stem has internodes and at the nodes the leaf and flower buds are formed. The leaves are trifoliate with a long, grooved and stiff petiole that is thickened at the base. Various leaf colours exist, from light green to dark green. Mostly two flowers that are papilionaceous, are attached to the peduncle by pedicels. The flowers are yellow in colour and flowering is indeterminate. Doku & Karikari (1971b) have identified a hollow at the tip of the keel through which ants enter both opened and unopened flowers.

During pollination and fertilization, the peduncle elongates to bring the ovaries at the soil level and after fertilization the pedicels penetrate the soil surface to form pods with either one or two seeds. The pods grow first in a round shape,

clustering the centre roots while others occupy the secondary roots. They are either green or purple when mature. The seeds are formed 40 days after fertilization. At maturity, the seeds vary considerably in colour and size and are smooth and extremely hard when dry. Seed colour varies from cream white, brown, yellowish brown, red, spotted, purple and black (Stephens, 2003).

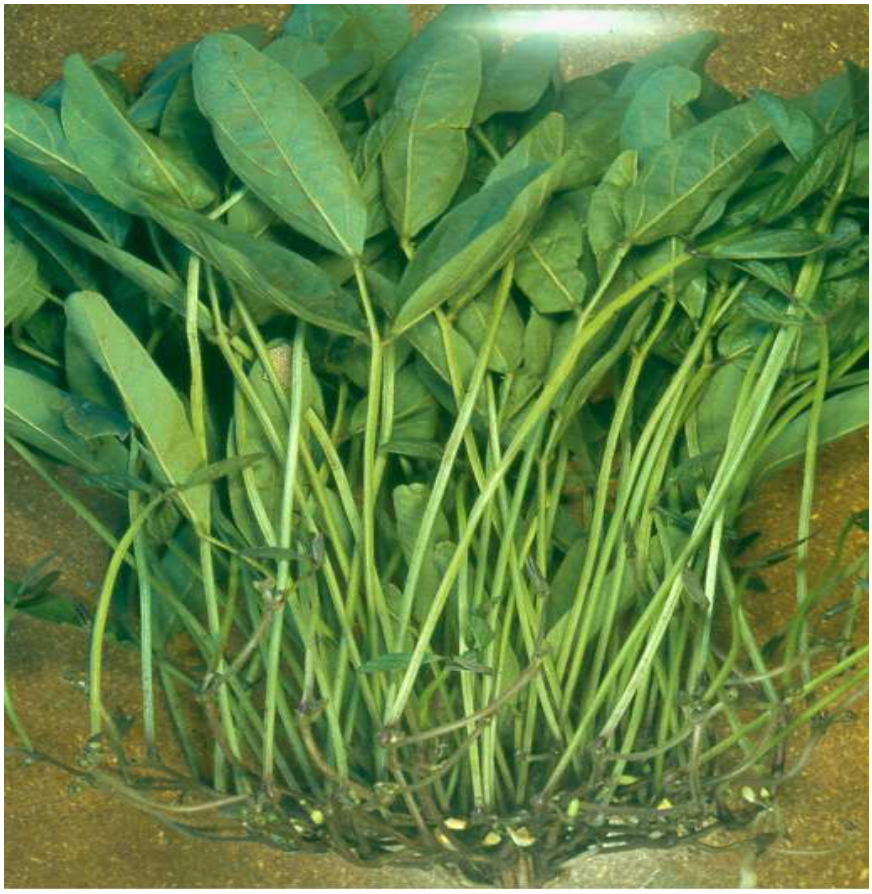

Figure 2.1 The bambara groundnut plant

2.5 Genetic resources and diversity

The centre of origin of bambara groundnut is likely to be in Africa (Hepper, 1963). This crop is widely distributed throughout the whole of Africa, but with a small amount being cultivated. The centre of genetic diversity of the crop is believed to be in countries such as New Caledonia, Philippines, India, Indonesia, Malaysia,

Sri-Lanka and South America, particularly Brazil (Rassel, 1960; Goli, 1997), where slaves must have introduced it during the time of the great slave trade.
The first collection and evaluation of bambara groundnut germplasm was carried out in the early 19th century (Anonymous, 1947). The Institute for Agricultural Research in Nigeria organized the second germplasm collection mission. About 80 accessions were collected, multiplied and maintained, and the most promising ones were subjected to yield evaluation trials. A wide range of differences in the seed coat colour, seed sizes, pigmentation around the eye, pod shape, growth habit, yield, shelling percentage, 50% days to flower, days to maturity and other characters were observed (Tanimu & Aliyu, 1990). The International Institute of Tropical Agriculture (IITA) in Nigeria contains an extensive amount of germplasm accessions (about 2035) in their genetic resources, which have been obtained from different countries.

In South Africa, there are approximately 327 accessions of bambara groundnut, with the Agricultural Research Council in Potchefstroom, Mpumalanga Department of Agriculture in White River and Agricultural Research Council in Roodeplaat having collected 200, 20 and117 respectively. Out of the 200 accessions in the ARC-GCI only 20 have been evaluated during the 1996-97 growing season and out of the 20, eight were used in this study; and from these entries crosses are currently being made with parent materials from Tanzania and Ghana. These collections possess a wide range of variation in shelling percentage, leaf colour and shape, seed size, seed colour, eye colour testa pattern (Cilliers & Swanevelder, 2002).

Knowledge of the genetic variation of the bambara groundnut accessions will be important for their efficient use in breeding programs, for studies on crop evolution, and for conservation purposes. Bambara groundnut shows a considerable amount of variability for various morphological, physiological and agronomic traits. According to Hayward & Breese (1994), a useful tool for

analysing the genetic structure of crop germplasm is the estimation of variation within and between populations of species.

Figure 2.2 Bambara groundnut accessions with different seed colour

2.6 Effect of the environmental conditions on production of the crop

Environmental factors play a major role in plant adaptation, because of their ability to influence the reproductive development of a genotype. There are various degrees in which these factors affect the crop and this depends on the genetic components of the crop. Poor harvest or crop failure may result due to biotic and abiotic stresses and this results in lack of stability of individual genotypes. Factors vary from location to location and from year to year in the same location, and their effect is reflected in the yields of crop. Therefore identifying the most stable and adapted cultivars is an important consideration. Bambara groundnuts tolerate a wide range of agro-ecological conditions (Collinson *et al.,* 1996).

2.6.1 Biotic conditions

Bambara serves as host to pathogens and insect pests, which cause a significant economic impact. Major biotic constraints to bambara production are disease, insects and viruses.

2.6.1.1 Diseases, pests and viruses that attack bambara groundnut

The crop has a tendency to resist pests and diseases. This could be because they produce their food below the soil and are free from attack by flying insects or maybe because they are mainly intercropped and isolated by crops such as maize. There are a number of pest problems and diseases found on bambara groundnut, but very little is known about the kind of pest and disease attacks and the extent of the damage to the plant, pods or seed. There are only a few authors who have reported on the pest and diseases of the crop. Swanevelder (1998) stated that *Meloidogyne incognita* and *M. javanica* are parasitic nematodes on bambara groundnut. Developing pods of bambara groundnut are damaged by *Piezotraachelus ugandum* (moth beetle), while larvae of the genus *Rivellia* cause damage to the root nodules. Various viruses have also been reported as being problems on bambara groundnut production. There are no chemicals registered for the control of diseases and pests on bambara groundnut in South Africa.

Diseases such as leaf spot, powdery mildew, fusarium wilt, leaf blotch and *Sclerotium roffsii* have been recorded on bambara groundnut in Zimbabwe. Fusarium wilt disease has been reported in Kenya as one of the major diseases limiting yields of the crop (Cook, 1978), and in South Africa most farmers experiences wilting problems in their fields. Signs of wilting diseases in the early stage, at the field in Potchefstroom are shown in Figure 2.3 and pod diseases are

shown in Figure 2.4. Cercospora is one of the major diseases that attacks the crop and usually occurs under irrigation. Foliar diseases reduce the vegetative biomass and thus the quality of the fodder. Bouriquet (1946) indicated that powdery mildew is a widely spread disease in Madagascar and has been named *Sphaerotheca voandzeia*. The disease is caused by the *Fungus erysiphepisi* and its presence is shown by white powder on the leaflets. Fusarium wilt has also been reported from Kenya (Cook, 1978) and Tanzania. Young seedlings are attacked by wilt in wet conditions, particular under waterlogged conditions.

The crop is susceptible to viruses such as cowpea mottle virus (Shoyinka *et al.,* 1978), cowpea mild mottle virus, *Voandzeia* necrotic mosaic virus (Fauquet *et al.*, 1984), white clover mosaic virus (Quantz, 1968) and two potyviruses (Bird, 1989; Bird & Corbett, 1988; Bock *et al.,* 1978). The potyvirus that was observed in Tanzania is related to peanut mottle virus and the potyvirus that is caused by seed borne diseases was observed in Togo.

In storage, bruchids (*Callosobruchus maculatus*) are the most important pest attacking the seeds of the crop (Swanevelder, 1998; Lale & Vidal, 2001). When the crop is stored whilst damp, mould sets in and weevils are able to attack the seeds. Most of the cultivars are resistant to weevil attack. Small animals like meercat and duikers attack the seed of the crop by digging up the plant in the field. The necessary control measures must be applied to protect the seeds in storage (Swanevelder, 1998).

Figure 2.3 Wilting disease of bambara groundnut in Potchefstroom

Figure 2.4 Bambara groundnut seeds with signs of pod diseases caused by fungi

2.6.2 Abiotic factors

In bambara groundnut, biotic stress causes yield reduction, but abiotic stress is the most limiting factor causing unstable yield. Important abiotic stresses are temperature, water, soil conditions, drought stress etc. This study concentrates mostly on weather and soil conditions.

2.6.2.1 Climatic conditions

Day length requirements for successive stages of the development are very important. Bambara groundnut is a typical short day plant and adverse variations could be observed as a result of long days (Nishitani *et al.,* 1988). The main factors affecting the development of many annual crops are photoperiod and temperature. The onset of podding is retarded by long photoperiod and also the onset of flowering is photoperiod sensitive (Linnemann, 1991; Harris & Azam-Ali, 1993; Linnemann & Craufurd, 1994). Photoperiods play a role in production of number of pods per plant, but this phenomenon depends on the type of the variety. Linnemann *et al.* (1995) found that some varieties had more pods under photoperiods of 10 to 12-h than the same varieties under 14-h, therefore it was concluded that in some varieties the shorter the photoperiod the higher the number of pods. Bambara groundnut is a fast growing plant, which requires warm temperatures and does not tolerate freezing temperatures at any stage of growth. An average day temperature that is ideal for the crop development is from 20 to 28^0 C. Extreme temperatures cause dying of the leaves, resulting in the reduction of the biomass yield. Wych *et al.* (1982) indicated that cool temperatures are conducive to longer seed filling periods and as a result increased yield in grain crops. The crop requires an average rainfall of about 600 to 700 mm during the growing season (Swanevelder, 1998) and too much rainfall at harvest may result in yield losses. The crop is most suited for hot dry areas where other crops cannot survive.

2.6.2.2 Soil characteristics

Soil texture and structure that enhance aeration in the soil determine the suitability of soils for bambara groundnut production. The seeds of bambara groundnuts are borne below the soil surface, therefore the choice of soil type is very important. The crop prefers well-drained, sandy loam soil because they can utilize lighter rain showers to greater advantage than clay soil and the soil cannot damage the seeds (Swanevelder, 1998).

2.7 Agronomical practices

2.7.1 Land preparation and earthing up

No tillage is needed when growing the crop in a well-drained, loose, aerated soil. The seeds can be sown directly after first removing the weeds and any trash from the previous crop. For compacted soil and weed infested areas, ploughing, followed by about two times of harrowing, is recommended to ensure good germination and stand. Sometimes the crop is planted on a flat surface or on ridges. According to Linnemann (1992), seedbed types do not affect the yields of the crop. In his studies, he found that there were no significant differences when the crop was planted on a flat surface or on ridges. Earthing up or ridging is a common practice performed by farmers in the whole of Africa and the main reason given for this, was that it has a positive influence on yield, but scientists at the Agricultural Research Council in South Africa did not find supporting evidence relating to those results (Swanevelder, 1998).

2.7.2 Plant population

Bambara groundnut reaction to population density varies with location. Linnemann (1992) reported that a population of 167 4000 plants ha^{-1} gave the highest yields in one location and lower yields in other locations. Swanevelder

(1998) indicated that the recommended spacing between the plants is 10-15 cm and between rows is 45-90cm to obtain optimum yields. He further reported that the highest yield was recorded in Swaziland, using a 50 cm in and between row spacing.

2.7.3 Planting date

Vegetative growth occurs in spring and early summer while the pods set only in late summer. If the crop is planted early or late, factors such as pod forming will be affected. Thus it is very important to know the correct planting date for the plant to produce higher yield, by being able to adapt well in an environment. Bambara groundnut produces good yields when planted October and November, especially after good rains (Swanevelder, 1998).

2.8 Emergence, 50% flowering and maturity of the crop

In studies of the crop conducted at the Agricultural Research Council in South Africa, several variations have been observed in terms of flowering between different lines (Swanevelder, 1997). The crop is a short day plant and when planted during long days, it results in delayed flowering or no flowering occurs and this depends on the type of cultivar. First flowering occurs about 30 to 45 days after planting (DAP) and it might continue until the plant matures, thus 50 % flowering takes about 80 DAP, but this depends on a cultivar. In some cultivars it is around 60 DAP.

The yield of a variety is influenced very much by its earliness. Late varieties are inherently capable of yielding more, but it is always risky to produce a late harvest, especially in many rainy regions on heavy soils, and farmers avoid this. Cultivars differ in the length of their growing period. The earliest variety takes about 110 to 120 days to mature (Swanevelder, 1998). The maturity of the bambara groundnut crop is dependant on the type of cultivar and climatic

conditions and therefore on an overall basis it takes three to six months to mature. The days to maturity are influenced by photoperiods. Linnemann *et al.* (1995) reported that under long photoperiods the time it takes to reach maturity is delayed in the bambara groundnut crop.

2.9 Yield and related characteristics

Yield is a quantitative characteristic that is controlled by a number of genes and thus it is considered a complex trait. It is determined by a number of components with a growth developmental sequence (Grafius, 1978). Thus components produced earlier have an influence on those that are produced later in the plant's growth cycle.

For the bambara groundnut crop, it is very important to have stable production, even in adverse, harsh growing conditions like low soil fertility, limited water availability and hot dry conditions. Yields are reduced to a lesser extent by these factors when compared to other crops (Linnemann *et al.,* 1995; National Academy of Sciences, 1979). According to Linnemann (1995), even in a favourable year, growers tend to prefer the certainty of a comparatively stable low yield of bambara groundnut than a chance of a once off high yield of groundnuts.

The yields of bambara groundnut vary from 50 to 4000 kg/ha. Average pod yields remain low and unstable, for example 400-1400 kg/ha unshelled pods in Zimbabwe (Heller *et al.,* 1995; Collinson *et al.,* 1999). Number of seeds per pod sometimes varies from one to three, depending on the cultivar. In South Africa, yields of over 3000 kg/ha have been obtained in field experiments (Swanevelder, 1998). However, in experiments done at the University of Nottingham under controlled environments, the crop was capable of producing a pod yield equivalent to 4000 kg/ha (Collinson *et al.,* 1999). However, there is no statistical

data in South Africa to compare with the figures in view of little attention being given to the crop.

There are no improved varieties of bambara groundnut currently in South Africa and farmers plant different landraces in different locations. Research has shown that through effective breeding, the yield level can be increased and the yield stability improved more rapidly and cost-effectively than the yields of other locally competing crops, such as peanut or cowpea, already at a higher yield level due to more research and marketing (Begemann *et al.,* 2002). However, breeding new lines can only be undertaken after the effects of individual components on yield and yield stability have been determined. Therefore it is very important to select varieties that are high yielding and stable in different agro-ecological conditions. Yields of bambara groundnut vary, depending on the variety cultivated. The area of production is very low due to many constraints. The constraints result in lower yields of the crop. Diseases and insect pests have not all been identified. Major factors associated with low production of bambara groundnut are as follows (Heller *et al.,* 1995; Swanevelder, 1998):

1. There are no improved cultivars and mainly landraces or local varieties are planted.
2. Low germination due to poor seed storage.
3. Breeding of cultivars through hybridization is very difficult due to the small flowers of the bambara groundnut.
4. Labour requirement is high due to the ambiguous character of the plant and therefore costly.
5. Small seeds result in poor or low yields, and therefore large seeds are recommended.

Development of high yielding and adapted varieties is one of the approaches to resolving the bambara groundnut shortages. The bambara groundnut plant resembles the groundnut. Ishag (1986) reported that yield components of

groundnut, which is a legume, are affected by environmental factors such as soil physical and chemical properties, temperature and available soil moisture beside plant population density. The most studied yield components of many crops are pod and kernel numbers and seed mass. In studies done by Tanimu & Aliyu (1990), shelling percentage and 100 seed weight were important characters correlated with grain yield and therefore used in selection of grain yield in Nigeria.

2.10 Nutritional value based on the protein content

Bambara groundnut is one of the leguminous crops that have been described as a complete food with sufficient amounts of nutrients. The crop is a major source of proteins, minerals and vitamins. Poulter & Caygill (1980), Linnemann (1987) and Arora (1995) stated that the crop provides an important source of proteins (16-25%), carbohydrates (42-60%), and fat (5-6%). Plant proteins provide nearly 65% of the world supply of proteins for humans from 45-50% cereals and 10-15% legumes (Mahe *et al.,* 1994), with legumes being a major source of proteins in tropical countries. Bambara groundnut genotypes overall provide 20-25% of proteins.

Maize is an unbalanced ration in the absence of animal products such as meat and milk, thus the inclusion of a legume in food would tend to balance the domestic diet. The crop's seed has a high lysine content that makes it a high-quality protein source and a good supplement to maize-based diets. The protein content is low when compared to other grain legumes such as soybean (35%) and cowpeas (30%), but it can still be improved through breeding of different varieties with high protein content. Improvement of the protein content will have a positive impact on the society by improving the nutritional balance diet of many people in the rural communities. In Botswana the protein content was found to be between 8.2 and 16.6 % (Heller *et al.,* 1995). This shows how varieties differ.

According to Obizoba (1991), bambara groundnut mixtures (BG-Corn) showed a nutritional superiority to pigeon pea when cooked. The bambara groundnut and pigeon pea had a protein content of 14.85% and 18.39% respectively, when compared to the cowpea variety which had the highest protein content of 22.87% in their study of nutritive value of the crops. They further indicated that the cowpea and bambara groundnut mixture have acceptable characteristics as sole sources of nutrients for infants or supplements for adults. Blends of sorghum-bambara groundnut and sweet potatoes have a good protein quality (Nnam, 2001).

2.11 Yield stability and genotype by environment interaction

Making selections in the presence of genotype with environment (gxe) interaction is a major problem facing many scientists. The process to develop genotypes that are stable and high yielding across different environments is an ongoing process all over the world. In every plant-breeding program breeders have to plant materials for a number of years in various locations in order to test stability of materials over a range of environments (Yan & Hunt, 1988). Yates & Cochran (1938) stated that agricultural experiments on the same, or group of factors, are usually carried out at a number of places and repeated over years, because the effect of most factors (varieties, fertilizers etc.) varies considerably between places and from year to year, due to differences in soil, agronomic practices, climatic conditions and other variations in the environment. There are cultivars that are less influenced by the productivity level of the environment, and then others whose performance is directly related to the productivity of the environment. According to Joppa *et al.* (1971), the sets of varieties will not rank the same for several given trials. Experimental error and genotype by environment interaction lead to differences expressed by changes in the rankings. To select for the best experimental lines, the yield trials should also be replicated. Therefore results from one year in the same place are of limited use even though they are accurate. According to Eberhart & Russell (1966), to obtain

useful information for stability parameters, cultivars must be grown in various localities. Assessing a cultivar's suitability for a given environment is based on its yield stability at the environment, yielding ability/potential, days to maturity etc. There are a number of measures that are used for studying the stability of genotypes in the presence of gxe interaction.

2.12 The importance of genotype by environment interaction and its effects

Dixon *et al.* (1994) stated that gxe interaction is the change in a cultivar's relative performance over environments, which results from differential response of the cultivar, to various edaphic, climatic and biotic factors. Gxe interaction occurs in two ways. Firstly the difference between genotypes vary without alteration in their rank i.e. gxe interaction is present because one cultivar yields more than another cultivar in all the environments, and secondly the ranking between cultivars changes across environments i.e. one cultivar will be more productive in one environment, while the other cultivar is more productive in another environment. Gxe interaction has never been studied in bambara groundnut, but literature from crops like soybeans and maize will be discussed.

Misra & Panda (1990) reported that inconsistent yield performance of cultivars in different environments may be a contributing factor to productivity due to large gxe interactions. Knauft & Wynne (1995) reported significant gxe interactions on yield and other agronomic traits in groundnut cultivars. Gxe is a phenomenon that is very important and is of significance to plant breeders, agronomist and farmers all over the world. Breeding materials can be selected and assessed on the basis of their different responses to the environments. The gxe interaction poses a serious problem in breeding programs because it is a factor, which can influence any stage of the program, like identifying appropriate sources or parent material. But it can also play a role in the expression of quantitative traits.

Studying of gxe interaction is very important to plant breeders because this interactionit can limit the progress in the selection process and since it is a basic cause of differences between genotypes for yield stability. Understanding the cause of gxe interaction is important to help in selecting varieties with the best adaptation and that can give stable yields. Linnemann *et al.* (1995) stated that it is important to understand crop development in relation to biophysical conditions and changes in season when selecting well-adapted genotypes and correct planting date. Varieties that show low gxe interaction and have high stable yields are desirable for crop breeders and farmers, because that indicates that the environment has less effect on them and their higher yields are largely due to their genetic composition. Therefore, introduction of bambara groundnut varieties that have a high yield and are stable over a wide range of environments will be a bonus to scientists and farmers (Tai, 1971).

Scientists define yield stability in many different ways and also use various stability measures to determine it. Blum (1980) defined yield stability as a measure of variation between potential and actual yield of genotypes across different environments. Fehr (1987) stated that yield stability of a cultivar is influenced by the genotype of individual plants and the genetic relationship between plants. It can be measured through analysis of variance procedures and regression analysis. Domitruk *et al.* (2001) indicated that the analysis of variance procedure is a useful tool for estimating the existence and magnitude of gxe interactions; however, the components of variances do not provide satisfactory explanation of the interaction. There are a number of suggested or proposed methods that can be used for stability measurement. Yates & Cochran (1938) proposed a purely statistical analysis, which was later used by Finlay & Wilkinson (1963) and Eberhart & Russell (1966). They used the analysis to detect and measure the magnitude of gxe interactions in barley and maize respectively.

2.13 Adaptation of crops

In breeding evaluation programs, selection of cultivars under high input conditions may be favoured compared to those selected in low input conditions (Ceccaralli, 1996). This could be why research on crop improvement has not had as much an impact on the small-scale farms compared to commercial farms. Falconer (1990) supported the idea of breeding for specific adaptation rather than broad adaptation. Ceccarelli (1996) found that breeding programs conducted under high input and uniform conditions may favour selection of cultivars adapted to good management and eliminate individuals adapted to poor conditions. In many cases, one or more factors limit production and prevent the full yield potential from being realized. Adaptation of a cultivar is affected by factors that vary from one location to another and from year to year. The effects of these factors are usually reflected in their yields. Therefore adaptation is an important factor that may increase productivity of a crop. It is better to replicate trials over years than over localities within years for effective comparison of cultivars, because cultivar x year interaction is greater than that of locality and locality x year (Patterson *et al.,* 1983). When breeding varieties that are adapted to different environments, a breeder has a choice of either breeding for similar ecological conditions or more variable conditions that include various environments (Finlay & Wilkinson, 1963).

Scientist should aim to produce cultivars that are able to withstand unpredictable environmental variations (Allard & Bradshaw, 1964). In the dry land agriculture of Africa, abiotic and biotic stress limit potential grain yields (Kenga *et al.,* 2003). The demand for legumes in Africa calls for an increase in production of bambara groundnut, which is one of the legumes grown in African countries. Poor grain yields may be associated with low yield stability (Fisher & Maurer, 1978; Sinha *et al.,* 1986).

2.14 Analysis of variance

Experiments in single environments do not allow the drawing of general conclusions regarding the tested genotypes; therefore they should be done across localities. Analysis of variance is carried out to partition the variation due to genotypes, environments and genotype by environment interactions.

2.15 Stability of performance

There are different concepts for stability. Lin *et al*. (1986) defined three types of stability. The first one was called type 1, which explained the deviation from the average genotype effect. In this type of stability the genotype is regarded to be stable if its environment variance is small. It refers to a genotype that performs equally well in all environments. Ideally this is what a breeder wants, but it is unrealistic and if it occurs the yield is very low. Type 2 was based on gxe interaction, in which a genotype is stable if its response to environments is parallel to the mean response of all genotypes tested. Any genotype with b=1 will be assumed to be stable. Type 3 refers to a genotype that has a small mean deviation. Therefore a genotype is stable if the residual mean square from the regression model on the environmental index is small. There is wide use of a regression coefficient of unity as a measure of stability when evaluating environmental effect on genotype. Breeding for broad adaptability requires a different interpretation and approach to the stability analysis procedure than breeding for specific adaptability (Hildebrand & Poey, 1985).

The first authors to conceptualise the stability analysis were Yates & Cochran (1938). They understood the potential to differentially recommend varieties based on their performance in different environments. Using environments that are of extreme conditions may be of value when evaluating genotypes for yield stability.

2.16 Measurement of stability

Methods have been developed for determining stability of performance of genotypes tested across a range of environments, that is for identifying stable genotypes. The first method used to measure stability was the regression analysis of Yates & Cochran (1938) and many researchers have studied stability analysis since then (Finlay & Wilkinson, 1963; Eberhart & Russell, 1966; Perkins & Jinks. 1968). Freeman & Perkins (1971) criticized the regression model. To make selection of genotypes precise and refined, and to reduce the effect of genotype and environment interaction, the yield and yield stability should be considered simultaneously. Ranking order of genotypes for yield when tested in several locations varies across the localities. That is the effect of gxe interaction, thus plant breeders have to take that into consideration when making selections.

2.16.1 Finlay and Wilkinson and Eberhart and Russell analysis

Finlay & Wilkinson (1963) described the characteristics of varieties with high and low stability regression parameters and related them to variety mean yield over environments. They found that a genotype with high stability has a regression coefficient of larger than 1 and that a value of lower than 1 can be regarded as poor stability. A genotype that is well adapted must have a regression coefficient of exactly 1 (b = 1). Eberhart & Russell (1966) defined a stable genotype as one with average response to the environment. They further said that a large gxe interaction limits progress from selection and to reduce this, the environments have to be stratified to make them more similar. In their study they found that gxe interaction is still large and they decided to select stable genotypes that interact less with the environments in which they are grown, and used only the more stable genotypes for the final stages of testing.

2.16.2 Ecovalence and stability variance

Wricke (1964) proposed ecovalence as a measure of phenotypic stability of genotypes, which includes only the interaction effects. It partitions the interaction sum of squares. Ecovalence depends strongly on the environments included in the test. Choice of specific environments or locations by plant breeders usually affects ecovalence. Small values show high ecovalence. The genotypes with a high phenotypic stability usually have low mean yields and are stable, because they are unable to exploit high yielding environments. Lin *et al.* (1986) described numerous methods for characterizing stability in the presence of gxe interaction.

The use of this measure assures that when selection is made, the importance of mean yield to stability is weighed. Avoiding low yields in a breeding program is mostly important and it is more important for breeders to develop materials that will be used by subsistence farmers who experience severe consequences as a result of low yields. In analysing gxe interaction, the regression approach is used often and is effective. The yield of a specific genotype in a given environment is regressed on another measurement of the environment. It is assumed that the regression coefficients for genotypes differ and are specific characteristics for the genotypes. Therefore, to calculate a regression coefficient, an environmental index is needed which is independent of the specific experiment and normally this is not available; therefore the average of all genotypes is used (Paroda & Hayes, 1971).

Scientists have been using different approaches in different crops to measure stability. Plaisted & Peterson (1959) were the first to attempt to obtain measurements of stability of individual lines. They estimated the variance components of cultivars x location interaction for each of the possible pairs of cultivars tested. Single ANOVA was firstly computed followed by a combined ANOVA over different localities where gxe interaction was obtained. The variety with the smallest mean value was taken as the one, which contributed the least

to gxe interaction and was thus considered the most stable genotype. This method was considered very important for measuring stability, but lacked dynamic estimates of stability and adaptability.

Various authors that had to estimate the stability of individual genotypes have used regression techniques. Finlay & Wilkinson (1963) developed a different model that was based on a linear regression. They said for each variety, a linear regression of individual yields on the mean of all varieties for each environment is computed. This model does not take into account the non-linear components. The method makes use of average yields of all varieties to describe environments. In 1966, two scientists, Eberhart & Russell, came up with a new stability model, which addresses both linear and non-linear components. The model was based on two stability parameters, which are the linear regression and deviation from the regression line. It utilizes the deviations from the grand mean of the yield over the various environments as production indexes of the environments. Other researchers such as Becker & Leon (1988) have adopted this model.

2.17 Additive Main Effects and Multiplicative Interaction (AMMI) and Principal Component Analysis (PCA)

The AMMI model has a good chance of predicting yield for new sites and years, giving a real advantage (Gauch, 1988). It is a multivariate analysis that is effective for many yield trials. The AMMI analysis uses analysis of variance (ANOVA) followed by a principal component analysis applied to the sums of squares allocated by the ANOVA to the line x environment interaction. These analyses partition the treatment degrees of freedom into model and residual. The model selectively recovers pattern while the residual selectively recovers noise (Gauch, 1988; 1990), resulting in adjusted treatment means that are predicatively more accurate than the unadjusted means (Gauch & Zobel, 1988; 1989). The AMMI addresses the treatment design and does not require any kind of

experimental design; therefore it can be collected under any design and used for ongoing decisions. It gives more accurate results than any other methods used for stability analysis. With this model, researchers can extract between-environment information or interaction. The advantage of using AMMI is that it offers a remarkably cost effective strategy for increasing the accuracy of yield estimates and can assist plant breeders to investigate the gxe interactions (Gauch & Zobel, 1996). The principal component analysis (PCA) is used to transform the data from one set of co-ordinate axes to another, preserving the original configuration of the set of points and concentrates most of the data structure in the first principal components axis. According to Crossa (1990), PCA is a generalization of linear regression that can overcome the pattern of univariate analysis by giving more than one statistic to describe the response pattern of a genotype. In an AMMI biplot the genotypes and environments are plotted on the same diagram, using the sign and magnitude of PCA1 values to show the specific interaction of individual genotypes and environments.

CHAPTER 3

MATERIALS AND METHODS

3.1 Locations

Multi-environment yield trials were conducted under rain fed field conditions during the 2004/05 growing season. There were financial and labour constraints, therefore only eight trials were planted. Four locations were used namely: University of Limpopo's Experimental Farm in the Limpopo province, the Agricultural Research Council-Grain Crops Institute (ARC-GCI) experimental station in Potchefstroom, the Department of Agriculture Experimental Station in Taung and ARC-GCI experimental station in Vaalharts at two different planting dates at each location. Potchefstroom was included because that is where the student was based, and for practical reasons the available infrastructure had to be used. Data of the Limpopo province were totally destroyed by a storm before harvesting could take place; therefore only data of six trials were used. The land for each location was ploughed a week before planting, by making a flat surface for alignment of genotypes. No fertilization was used in any localities.

Potchefstroom

The trial was planted on clay soil. The location received much rain during the early stage of development (Table 3.3) and at some stages the field was waterlogged and some plants did not survive. Fusarium wilt also occurred.

Taung

The trial in Taung was conducted on a sandy soil. The location received the least rain compared to other locations (Table 3.3). The Taung trial was damaged by meercats during the growing season.

Vaalharts

No complications were encountered on this trial during the growing season. Enough rainfall was obtained for good plant growth and yields. The location was irrigated from November to March 2005 (Table 3.4) and received the highest rains (Table 3.3) compared to the other localities.

3.2 Materials

Eight accessions obtained from the ARC-GCI in Potchefstroom were planted during the 2004-2005 growing season. Some of the genotypes were given names by the local people and farmers who cultivate them: SB1-1 (Thutlwa), SB4-4, SB7-1 (Phala), SB8-1, SB9-1 (Tshesebe), SB16-5A, SB19-3 (Tshukudu) and SB20-2A (Kubu), that vary in colour and other characteristics. A list of the genotypes used in the study with their characteristics is given in Table 3.1. These materials represent genotypes that are used by breeders at the ARC-GCI for the improvement programs. They were selected from the 20 accessions that were planted during the 1996-1997 growing season in 10 replicated trials. The criterion used for selecting the genotypes was availability of the seeds. The seed was packed in brown bags for each location and stored in cold storage before planting. The seeds were not treated.

3.3 Experimental details

The experiments were conducted during the cropping season of 2004-2005. The trials were managed as follows:

Two different planting dates, with a two-week interval were used for planting of the trials in each environment, in order to determine the effect of planting date on bambara groundnut production (Table 3.2). Land was demarcated using ropes and sticks. The eight genotypes were planted manually in a Randomized Complete Block Design, with three replications. The hoe was used to open the

rows about 5cm deep and the seeds were placed 7.5cm apart in the rows and only one seed per hill was planted. In each experimental plot, 4 rows 90cm apart and 5m long of each accession were planted within a plot of 18m^2. Each genotype was seeded at a population density of 266 plants per plot with a total of 48 plots per locality. Germination occurred at 14 days after sowing. The fields were kept free of weeds manually using a hand hoe. Irrigation was applied in the Vaalharts plots when the plants showed signs of drought stress. Agro-ecological data for all the localities is shown in Table 3.2.

3.4 Measurements

For each plot the agronomical data recorded were: Days to 50% flowering (from the time of sowing until 50% of the plants had at least one open flower), days to physiological maturity, stand count at emergence (the number of plants germinated in each plot were counted) and stand for each harvested area (number of plants were counted and recorded prior to harvest). The border rows were used for destructive sampling. Plants were sampled from the experimental plots at different planting dates (19, 20 and 21 April) and (4, 5 and 6 May) in Potchefstroom, Taung and Vaalharts. During sampling, four plants were dug up from the border rows within the plots. Data recorded was number of pods per plant (counting the pods), 100 seed weight (100 seeds were counted, picked up randomly and weighed to the nearest 0.1g) and root weights (removed from the four harvested plants and weighed to the nearest 0.1g).

3.4.1 Harvesting

The plants were harvested on the 09th and 23rd at Potchefstroom, 10th and 24th at Taung and 11th and 25th May 2005 at Vaalharts. Harvesting was done manually by digging up of the whole plant using a spade and picking up the remaining pods from the soil. The pods were separated from haulms and air-dried. The pods were cleaned to remove soil and inert matter. Total dry matter and seed

yields were determined by harvesting two centre rows. Total fresh pod and fresh haulms were determined in the field. From the fresh material, 500g seeds and 500g haulms were sampled. The 500g seeds and 500g haulms samples were later oven dried for 72 hours at 65 ^{0}C to determine dry weights. The fresh and dried weights were used in determining the total grain and haulm yield (expressed as kilograms per hectare).

3.4.2 Protein content

Protein content was determined in duplicate for the first planting date at all three localities to indicate the range of protein content at each locality. The data set was reduced due to the prohibitive cost of the analyses. Protein content was analysed using an automatic Protein/Nitrogen Determinator LECO FP-528. Seeds were milled to a flour. Duplicate flour samples of about 3 g were dried in an oven at 105 ^{o}C for 72 hours. Then the dried samples were cooled in a desiccator containing dry Silica gel for an hour. Samples of 0.30 g were weighed immediately after removal from the desiccator and then were loaded into the protein analyser.

3.5 Statistical analysis

Statistical computations and estimation were carried out using Agrobase (2000). Each location in a given season was considered as an individual environment. Data obtained from each location was initially analyzed separately by running a single ANOVA and thereafter data were pooled to perform the combined analysis of genotypes across locations. Analysis of variance was carried out to partition the variation due to genotypes, environment and genotype by environment interaction. Five stability methods were used in the study to identify stable genotypes.

1) Eberhart & Russell (1966),
2) Cultivar Superiority (Lin & Binns, 1988)

3) Wricke's Ecovalence (1963),
4) Additive Main Effects and Multiplicative Interaction (Gauch, 1988),
5) AMMI stability value (Purchase, 1997).

The grain yield of genotypes in each environment was regressed on an environmental index, measured by the average performance of all genotypes in that environment. Data processing for determining gxe interaction was done using the AMMI model.

$$\text{AMMI Stability Value (ASV)} = \sqrt{\left[\frac{IPCA1\ \Sigma\ of\ Squares}{IPCA2\ \Sigma\ of\ Squares}(IPCA1score)\right]^2 + [IPCA2]^2}$$

Table 3.1 List of genotypes with agronomical characteristics and descriptors according to the ARC germplasm catalogue.

Entries	Accession no:	Source	Seed colour	Leaf colour
SB1-1	66	NO 12, J16, 77154	Black small spots on brown background without eye pattern	Light green
SB4-4	64	Ncluhu, 011, 81139	Black	Dark green
SB7-1	36	J13, 76470	Dark red	Dark green
SB8-1	69	DL/58/583, C4, 62170	Black small spots on brown background with testa pattern	Light green
SB9-1	15	J12, 76465	Light brown	Dark green
SB16-5A	21	J12, 76462	Purple	Dark green
SB19-3	61	J13, 76467	Dark purple	Dark green
SB20-2A	49	NO V3, J12, 76464	Cream with an eye-pattern	Purple green

Table 3.2 Agro-ecological data, 2004-2005 growing season.

Locations	Planting dates	Soil type	Latitude	Longitude
Potchefstroom1= (Loc1) 2= (Loc4)	08 November 22 November	Clay soil	-26.7361	27.0757
Taung 1= (Loc2) 2= (Loc5)	09 November 23 November	Sandy	-27.5500	24.7670
Vaalharts 1= (Loc3) 2= (Loc6)	10 November 24 November	Sandy	-27.9500	24.8300

Table 3.3 Monthly total rainfall and average temperatures for multilocational trials during 2004-2005.

Potchefstroom				Taung			Vaalharts		
Month	Rain	Tmax	Tmin	Rain	Tmax	Tmin	Rain	Tmax	Tmin
November	51.5	31.6	15.6	29.4	34.8	16.7	51.6	34.4	16.9
December	91.0	29.7	16.5	98.6	33.4	18.0	183.9	32.8	16.9
January	188.0	29.7	17.3	79.4	32.1	18.0	93.0	32.3	17.5
February	69.6	29.4	16.6	0.00	33.6	18.9	91.9	32.2	17.4
March	56.7	26.9	13.6	78.8	29.1	14.9	83.9	28.6	14.3
April	59.2	23.7	10.4	62.2	25.0	10.8	59.5	24.8	10.1
Total	516	171	90	151.2	188	97.3	563.8	185.1	93.1

Table 3.4 Irrigation data for Vaalharts for two planting dates in the 2004-2005 growing season.

Dates	Date1	Date2
First	20 December	10 January
Second	03 January	19 January
Third	10 January	21 January
Fourth	19 January	07 February
Fifth	21 January	15February
Sixth	07 February	28 February
Seventh	15 February	08 March
Eighth	28 February	31 March
Nineth	08 March	N/A
Tenth	31 March	N/A

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of variance for separate trials

Mean squares value of the entries at Loc1 exhibited highly significant (P≤0.01) differences for haulm yield, 100 seed and number of days to maturity and also a significant variance for grain yield (Table 4.1). But number of pods per plant, 50% days to flowering and root weight showed no significant differences between genotypes. The coefficient of variation of legumes on the whole was reported to be very high, 35.9% in pea and 41.2% in faba beans (Golaszweski et al., 2005).

Loc2 indicated both highly significant (P≤0.01) and significant (P≤0.05) differences between entries for all traits, grain yield, haulm yield, 100 seed weight, number of pods per plant, root weight, and number of days to maturity, except for 50% days to maturity.

A highly significant (P≤0.01) difference and significant (P≤0.05) difference were exhibited between genotypes for grain yield, 100 seed weight, root weight and number of days to maturity at Loc3. There was no variation between genotypes for haulm yield, number of pods per plant and 50% days to flowering.

In Loc4, six characteristics showed no significant differences for both entries and blocks, with exception of number of days to maturity, which showed highly significant (P≤0.01) variance between the entries.

For Loc5, the mean square values indicated highly significant (P≤0.01) differences between the genotypes for almost all the traits measured except for root weight and 50% days to flowering.

At Loc6 there was a highly significant (P≤0.01) variance for grain yield, haulm yield and days to maturity between genotypes. The genotypic effect of the remaining traits and the block effects, showed no significant differences, indicating that the genotypes were uniform for the traits that showed no significant difference and also that the field was uniform between the blocks.

4.1.1 Mean values for the separate trials

Loc1

Genotype mean values for seven agronomic traits are exhibited in Table 4.2 (a). The highest grain yield was produced by SB 20- 2A, SB19-3 and SB8-1 while the lowest yield was produced by SB16- 5A, SB9-1 and SB7-1. Yield of genotypes varied from 1696 to 613 kg/ha. Loc1 had the highest means for grain yield, haulm yield, and 100 seed weight when compared to Loc4. The plants flowered early and matured early at Loc1 than at Loc4 [Table 4.2(a) and Table 4.2 (d)]. Loc1 and Loc4 resulted in low grain yields because the soil type was not good for cultivation of the bambara groundnut crop. The plants were also attacked by fusarium wilt due to higher temperatures. There was higher rainfall in the early stages of growth, which resulted in waterlogged plots.

The haulm yield ranged from 2570 to 7458 kg/ha between the genotypes. SB20-2A gave the highest yield of 7458 kg/ha (significantly higher than the other entries) followed by SB19-3 with 7049 kg/ha and SB8-1 with 5901kg/ha. The above three genotypes performed significantly better than SB1-1 (2570 kg/ha), SB7-1 (2739 kg/ha) and SB8-1 (3349 kg/ha). The average haulm yield of the genotype is 4722 kg/ha. In this location SB7-1, SB9-1 and SB16-5A gave the lowest yield for all traits measured except for SB16-5A, which was the third best yielder with regards to the number of pods per plant. The highest number of pods for a plant does not necessarily guarantee the highest yield.

Hundred seed weight is an indication of the seed size of a genotype and does not give the measure of average seed yield. Hundred seed weight was

significantly affected by genotype (Table 4.1). As shown in Table 4.2 (b) the average was 43g. The genotype weights varied from 50g to 35g. SB8-1 had significantly higher seed weight than SB16-5A, SB20-2A and SB7-1. The second and third ranking genotypes were SB19-3 and SB1-1. Number of pods per plant did not show any significant variation between genotypes. SB1-1 and SB7-1 had more pods per plant (164), followed by SB16-5A, SB20-2A and SB19-3. Genotypes with the lowest number of pods were SB19-3, SB4-4 and SB8-1.

SB4-4 was the first genotype to achieve 50% flowering followed by SB8-1 and SB19-3, with SB16-5A and SB7-1 being the last genotype to flower. Means showed a small variation between the genotypes with an average of 66 days after planting. With regards to days to reach physiological maturity, means showed significant variation, ranging from 120 to 151days. SB20-2A was the first genotype to reach maturity at this location, followed by SB7-1 eight days later. SB19-3 was a late maturing type at 151 days and SB7-1 was a medium maturing type.

Loc2

Table 4.2(b) indicates means of genotypes for Taung1. The genotypes showed significant differences for both grain and haulm yield. SB4-4, SB20-2A and SB1-1 gave the highest grain yield; while SB20-2A, SB19-3, SB8-1 and SB7-1 had the highest haulm yield. Genotypes showed variation for grain yield from 429 to 2554 kg/ha and for haulm yield from 2514 to 7018 kg/ha.

Significant differences in 100 seed weight, root weight and number of pods per plant were observed between the genotypes. SB1-1 and SB4-4 had the highest 100 seed weight, but ranked third and fourth in number of pods per plant. The genotypes with the largest number of pods per plant were SB20-2A and SB16-5A, but they had the lowest 100 seed weight. Root yield is the amount of absolute dry matter accumulated in the roots. The genotype with the lowest root

weight was SB1-1 whereas SB20-2A and SB16-5A gave the highest root weights.

SB20-2A and SB7-1 were the earliest maturing types. Number of days to physiological maturity was related to 50% flowering; because the plants that flowered first were also early maturing. The lowest yield was obtained at this location because Meercats damaged the plots by digging in the soil and destroying the root system, by so doing cutting the nutrient supply to the plants and resulting in plant death.

Loc3

SB4-4 had significantly higher grain yields than other entries except SB1-1. SB1-1 and SB19-3 ranked second and third (Table 4.2 c). Average grain yield was 2609 kg/ha and varied from 1936 to 3636 kg/ha. There was no variation between genotypes for haulm yield.

SB1-1 had a significantly higher 100 seed weight than the other genotypes, but the genotype that had larger seeds had a lower number of pods per plant. Ayisi (2000) reported that increased seed yield resulted from large seeds. For root weight, SB20-2A had the highest value. SB20-2A and SB1-1 were the first genotypes reaching 50% flowering and are regarded as early and medium maturing respectively, except for SB7-1, which reached 50% flower at 70 days and matured early. Grain yield for Vaalharts was higher because the experiment was supplemented with irrigation. Also the soil type was very good for the cultivation of bambara groundnut.

Loc4

Table 4.2 (d) summarizes the mean performance of the tested genotypes for Potchefstroom2 and it indicated that SB7-1, SB19-3 and SB20-2A had the highest grain yield and SB1-1, SB8-1 and SB16–5A the lowest yield respectively. The means of the genotype varied from 1341 to 454 kg/ha and had an average

of 927 kg/ha. The lowest haulm yield was observed for SB7-1, which had high grain yield. But this was not the case for other genotypes since SB19-3 and SB20-2A had the highest grain yield and haulm yield simultaneously. The average haulm yield value of the genotypes was 4105 kg/ha, and means ranged from 2799 to 5149 kg/ha.

Hundred seed weight was not affected by genotype (Table 4.1). This means that there was no variation between genotypes for 100 seed weight. SB1-1 had larger seeds, the largest number of pods per plant and the highest root weight when compared to the other genotypes. SB4-4 had the second largest seeds, but it had the least number of pods per plant. SB20-2A, SB16–5A and SB8-1 were small seeded genotypes that did not differ significantly and gave the least number of pods per plant and lowest root yield, except for SB8-1 that ranked second with the largest number of pods per plant and higher root weight. SB20-2A was the earliest to 50% flowering and maturity period compared to other genotypes. SB19-3, a late maturing and SB7-1, a medium maturing genotype ranked second and third to 50% flowering. Days to physiological maturity was significantly different between genotypes. The variation between genotypes ranged from 125 to 153 with an average of 141 days to maturity. SB20-2A reached physiological maturity faster at 125 days when compared to SB19-3 with 153 days to maturity.

Loc5

A summary of mean performance of bambara groundnut genotypes for Taung2 is indicated in Table 4.2 (e). Grain yield varied from 1618 to 346 kg/ha at this location. SB1-1 and SB4-4 had the highest grain yield of 1618 and 1431 kg/ha respectively and differed significantly from lowest yielding genotypes, which were SB8-1, SB7-1, SB9-1, SB16-5A and SB19-3 respectively. Baryeh (2001) has reported an average yield of 850 kg/ha, which is not much different from what this study found. SB1-1 and SB4-4 gave high haulm yields of 6937 and 6718 respectively. Means varied from 6937 to 2676 kg/ha, with an average yield of

4802 kg/ha. Again SB7-1 gave the lowest haulm yield. This could be attributed to the relatively small type of plant which is characterized by small leaves, stem and root weight. This shows that it is very important to consider all plant attributes when selecting the best genotype.

Average 100 seed weight at this location was 41.7, with the highest seed weight obtained by SB1-1. SB16-5A is regarded as a small seeded type since it had the lowest 100 seed weight. The 100 seed weight ranged from 34.7 to 48.3g. The low 100 seed weight was attributed to poor crop performance and quality of the seeds. 100 seed weight varies greatly between genotypes because of their different seed sizes and compositions.

The number of pods per plant is related to the number of flowers produced, the proportion of flowers that initiated pods, and proportion of pods that survived to produce grain-bearing pods. The number of pods per plant varied between the genotypes. SB9-1 produced the highest number of pods per plant, which was more than the average pod production across the bambara groundnut genotypes. SB20-2A was the second best genotype for pods per plant. Means ranged from 91 to 260 pods per plant with an average of 157. The genotypes with the least pods per plant were SB1-1, SB16-5A and SB19-3. The highest mean number of pods per plant differed significantly from the genotypes that had the lowest number of pods per plant. Just like at Loc2, SB16-5A ranked the highest in terms of root mass accumulation. SB9-1 accumulated a lower proportion of root biomass when compared to other genotypes. The other remaining genotypes did not differ from one another with regards to root weight. The average time to 50% flowering was 69 days after planting. The number of days from sowing to 50% flowering was from 63 to 76 days after planting. SB1-1 and SB19-3 were the earliest genotypes. SB7-1 was the last genotype to obtain 50% flowering. The total time from sowing to maturity ranged from 128 to 152 days after planting. SB20-2A and SB1-1 exhibited the earliest maturity of 128 and 134 days after planting. The number of days to physiological maturity was

similar between the late maturing genotypes. Between the genotypes SB1-1 and SB8-1 across the genotype were the medium maturing genotypes, with an average of 143 days from planting to maturity.

Loc6

Table 4.2(f) shows the averages of seven characteristics of bambara groundnut genotypes for Vaalharts2. Grain yields, haulm yields and days to physiological maturity showed significant difference between the genotypes. SB4-4 and SB1-1 were the first and second best genotypes that gave the highest yield of 5175 and 4359 kg/ha respectively. The yield of 5175 kg/ha is very high considering the highest yield per genotype that has been obtained in other studies. These high yields reflect the highest rainfall in Vaalharts, the supplementation of irrigation during the growing season and the good soil type. The average grain yield obtained was 3085 kg/ha, which is also high compared to other locations. The average yield obtained in this locality is similar to those obtained under field conditions by Swanevelder (1998). SB9-1, SB16-5A and SB20-2A had the lowest yield and showed no similarity between each other. This locality had the highest average haulm yield of 10407 kg/ha when compared to other localities. This location was under irrigation and was not attacked by diseases as at Taung and Potchefstroom. The soil type was good for the cultivation of the crop and the genotypes responded well to this environment, with the lowest haulm yield of 8894 kg/ha and an average of 10407 kg/ha between the genotypes. The yield varied greatly between the genotypes.

The genotype with the highest 100 seed weight was SB1-1. This is attributed to good quality seeds and higher yields. SB16-5A and SB20-2A ranked second and third. Hundred seed weight is a measure of seed size. SB7-1 had the lowest 100 seed weight due to small seed type, and not because of poor yield. The average 100 seed weight between genotypes was 51g; therefore all the remaining genotypes in Table 4.2 (f) were regarded to be small seeded types at this locality. The means ranged between 46g to 57g. SB16-5A produced the highest number

of pods per plant. The genotypes had means that ranged from 313 to 168 pods per plant, with an average of 214 pods per plant. Four genotypes namely, SB1-1, SB8-1, SB20-2A, SB4-4 and SB19-3 had the lowest number of pods per plant.

Root biomass accumulation of SB16-5A was higher than that of SB20-2A, SB1-1 and SB8-1, which had the lowest root yield. The average was 8.5g and the range from 6.3 to 10.7g. The days to 50% flowering was not significantly different between the genotypes and was between 61 and 69 days after planting. SB16-5A, SB9-1, SB8-1 and SB20-2A were the first genotypes to obtain 50% flowering. The slowest genotype to reach 50% flowering was SB4-4 with 69 days after planting. This differed significantly from the fastest genotype. SB20-2A was the only early maturing genotype, 127 days after planting. Medium maturing genotypes were SB7-1, SB8-1, and SB1-1. The means of the genotypes ranged between 127 to 150 days, with an average of 142 days after planting. The number of days to reach maturity varied greatly between the early and late maturing genotypes.

4.1.2 Genotype rankings

Grain yield in all six localities indicated a high variation between the genotypes, as rankings were different from one location to the other. SB20-2A gave the highest yield at both Potchefstroom and Taung. It ranked first and second at Loc1 and Loc5 and ranked second and third at Loc2 and Loc5, respectively, but it had poor yields at Vaalharts under irrigation. SB8-1 was the third best in Loc1, but was the poorest in all the other locations. SB19-3 gave highest yield at Loc1, Loc3 and Loc4. It gave the lowest yield of 999 and 346 at Loc2 and Loc5 respectively. The highest yield at Loc3, Loc2 and Loc5 was obtained by SB4-4 and SB1-1. Swanevelder (1998) reported yields of about 3085 kg/ha. The highest grain yields of 4000 kg/ha for bambara groundnuts were obtained under controlled environments (Collinson *et al.,* 1999). Findings indicated that the ranking of some genotypes change from one location to another, suggesting

significant genotype x location interactions [Table 4.2(a) to 4.2 (f)]. The results emphasise the importance of genotype and location as yield predictors for higher crop yield production.

Table 4.1 Mean square values for seven characteristics of bambara groundnut measured in six localities during the growing season 2004-2005.

Source of Variation	Grain yield	Haulm yield	100 seed wt	Number of pods/plant	RW	DF	DM
Loc1 Entry	502608.8*	11537062.7**	61.9**	3775.8	1.0	15.8	256.9**
Block	95456.4	957711.1	27.4	434.0	3.0*	22.2	11.2
C.V.	36.37	31.71	8.65	35.09	13.55	9.84	1.13
Loc2 Entry	1470216.4**	4567593.5*	78.8*	12883.4**	4.1*	50.5	294.5**
Block	173078.0	6984710.8*	0.04	6220.1	1.1	173.4	5.2
C.V.	28.16	23.49	10.95	33.91	16.37	11.04	1.36
Loc3 Entry	1047727.8**	11060179.8	46.9*	4376.9	8.5**	27.1	230.2**
Block	82343.6	2171693.4	1.5	1583.3	1.6	7.0	19.8
C.V.	18.15	23.98	7.78	29.97	11.87	6.21	2.40
Loc4 Entry	292705.2	2761966.6	32.7	3119.3	0.9	8.2	238.2**
Block	67348.2	4416005.3	28.3	836.8	0.8	43.6	12.7
C.V.	36.02	34.73	11.16	26.13	16.53	8.80	1.82
Loc5 Entry	581601.7**	8339557.6**	64.0**	9653.8**	2.99	60.8	232.4**
Block	77859.0	4935.2	95.8**	810.7	1.16	58.0	10.8
C.V.	32.54	24.13	9.13	20.09	15.41	7.12	2.34
Loc6 Entry	4084127.3**	21503127.0**	41.9	8050.9	5.9	30.9	192.3**
Block	94833.4	1672126.2	32.4	5875.1	2.2	24.5	0.1
C.V.	16.46	17.06	8.66	36.30	24.70	8.64	1.10

*p ≤ 0.05, ** p ≤ 0.01

Table 4. 2 (a) Mean performance of the eight bambara groundnut genotypes at locality one at Potchefstroom (Loc1).

Genotype	Grainyield (kg/ha)	Haulmyield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	1017	2570	45.67	164	7.0	66	137
SB4-4	899	3377	45.00	83	6.7	61	140
SB7-1	760	2739	42.00	164	5.6	67	128
SB8-1	1512	5901	50.00	90	7.0	64	141
SB9-1	698	3348	43.67	80	5.7	66	140
SB19-3	1404	7049	46.00	137	6.0	65	151
SB16-5A	613	5332	35.00	147	6.3	69	138
SB20-2A	1696	7458	39.67	141	7.0	66	120
Mean	1075	4722	43.00	126	6.4	66	137
C.V.%	36.37	31.71	8.65	35.09	13.55	9.84	1.13
$LSD_{(0.05)}$	562	2153	5.39	ns	ns	Ns	2

Table 4. 2 (b) Mean performance of the eight bambara groundnut genotypes at the first locality of Taung (Loc2).

Genotype	GrainYield (kg/ha)	HaulmYield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	1309	4372	49.3	147	6.0	63	140
SB4-4	2554	2514	43.2	132	7.7	64	142
SB7-1	706	4629	38.0	120	7.3	53	127
SB8-1	429	4699	36.7	51	6.0	65	145
SB9-1	474	4495	31.6	106	7.3	68	144
SB19-3	999	4791	40.7	84	6.2	71	149
SB16-5A	716	4001	39.6	167	8.6	69	147
SB20-2A	1449	7018	39.0	270	9.1	58	122
Mean	1080	4565	39.8	104	7.3	64	140
CV%	28.16	23.49	10.95	33.91	16.37	11.04	1.36
$LSD_{(0.05)}$	437	1542	6.26	65	1.7	ns	2

Table 4. 2 (c) Mean performance of the eight bambara groundnut genotypes at the first locality of Vaalharts (Loc3).

Genotype	GrainYield (kg/ha)	HaulmYield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	3080	10649	57.3	204	7.3	64	135
SB4-4	3636	9474	52.7	201	9.0	66	135
SB7-1	2571	6360	46.6	296	7.0	70	122
SB8-1	2531	13017	51.7	246	7.0	69	145
SB9-1	2116	10663	49.7	262	7.7	70	140
SB19-3	2972	9617	47.3	218	7.3	70	144
SB16-5A	2033	8986	56.6	176	8.6	71	135
SB20-2A	1936	11072	49.7	236	12.0	64	122
Mean	2609	9980	51.5	230	8.2	68	135
C.V.%	18.15	23.98	7.78	29.97	11.87	6.21	2.40
LSD $_{(0.05)}$	681	ns	5.7	ns	1.4	ns	4

Table 4. 2 (d) Mean performance of the eight bambara groundnut genotypes at the second Potchefstroom locality (Loc4).

Genotype	GrainYield (kg/ha)	HaulmYield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	454	4542	46.3	229	7.0	70	139
SB4-4	1010	4413	45.0	127	6.3	70	148
SB7-1	1341	2799	42.7	151	6.0	69	135
SB8-1	578	3141	38.3	166	7.2	73	137
SB9-1	1039	4762	41.0	160	5.7	70	149
SB19-3	1215	5012	43.7	137	6.6	68	153
SB16-5A	714	3019	38.3	142	6.3	69	143
SB20-2A	1062	5149	38.0	135	6.0	68	125
Mean	927	4105	41.7	156	6.4	70	141
C.V.%	36.02	34.73	11.16	26.13	16.53	8.80	1.82
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns	3.70

Table 4. 2 (e) Mean performance of the eight bambara groundnut genotypes at the second Taung locality (Loc5).

Genotype	GrainYield (kg/ha)	HaulmYield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	1618	6937	48.3	91	6.7	63	139
SB4-4	1431	6718	42.0	182	7.3	68	147
SB7-1	669	2747	47.2	177	6.6	76	134
SB8-1	690	5925	37.0	144	6.7	73	141
SB9-1	546	2676	42.0	260	6.3	68	152
SB19-3	346	5040	42.0	106	7.0	64	150
SB16-5A	355	3732	34.7	104	9.0	66	151
SB20-2A	858	4638	40.3	188	8.7	72	128
Mean	814	4802	41.7	157	7.3	69	143
CV%	32.54	24.13	9.13	20.09	15.41	7.12	2.34
LSD $_{(0.05)}$	399	1665	5.4	45	ns	ns	4

Table 4. 2 (f) Mean performance of the eight bambara groundnut genotypes at the second Vaalharts locality (Loc6).

Genotype	GrainYield (kg/ha)	HaulmYield (kg/ha)	100seed wt (g)	Number of pods/plant	Root wt (g)	50% Flower	Maturity days
SB1-1	4359	14807	56.7	168	7.7	65	141
SB4-4	5175	12621	49.0	196	8.3	69	150
SB7-1	3199	10756	46.3	185	9.3	61	137
SB8-1	2798	12216	51.0	177	7.7	62	138
SB9-1	1807	7647	48.7	274	8.3	61	146
SB19-3	3056	8894	46.7	211	10.0	64	150
SB16-5A	2016	7041	54.0	313	10.7	58	148
SB20-2A	2270	9274	53.6	187	6.3	62	127
Mean	3085	10407	50.8	214	8.5	63	142
C.V.%	16.46	17.06	8.66	36.30	24.70	8.64	1.10
LSD $_{(0.05)}$	730	2554	ns	ns	ns	ns	2

4.2 Correlation matrix analysis between four traits of bambara groundnuts

4.2.1 Linear correlations for separate trials

The relationship between yield and morphological related traits associated with seed yield for six separate trails is presented in Table 4.3 (a) to 4.3 (f). Ofori (1996) reported that seed yield is a quantitative characteristic, which is largely influenced by the environment and has low heritability. Total grain yield is a measure of seed weight, number of pods per plant, number of seed per pod and number of plants per unit area. Yield components are an important measure of crop yield and they vary depending on location and genotype. It is very important to understand the associations of yield components as influenced by location (Evans, 1993).

In Table 4.3 (a), both haulm yield and 100 seed weight correlated moderately positively with grain yield. Seed weight varied significantly between genotypes because of different seed sizest. Lack of significant relationship between numbers of pods per plant and seed yield was unexpected. In literature it was reported that the number of pods per plant is closely associated with legume seed yield (Sinha, 1982; Ayaz *et al.,* 2001). Days to maturity and 50% flower had a negative correlation with grain yield and the findings are similar with those found by Hoque *et al.* (1993).

The results showed that 100 seed weight was the only trait that showed a significant relationship with grain yield (Table 4.3b). Significant ($P \leq 0.05$) positive correlation was shown between number of pods per plant and root weight. A moderate ($P \leq 0.05$) negative correlation was observed between the number of pods per plant with root weight, 50% flowering and days to physiological maturity; and also between haulm yield and days to maturity. The significant negative correlation for number of pods per plant in relation to 50% flowering indicated that, even though most of the plants reached 50% flowering, the proportion of

flowers that produced pods and pods that survived to produce grain-bearing pods was lower.

Root weight and 100 seed weight showed significant positive association with pod per plant and 50% flowering and DM respectively (Table 4.3c). In Table 4.3(d), highly significant (P≤0.01) positive correlation was shown between number of pods per plant and root yield. Ayisi (2000) reported increased grain yield due to greater seed weight in his study. Table 4.3(e) showed a highly significant (P≤0.01) positive correlation between grain yield and haulm yield, and for grain yield and 100 seed weight. The results indicate that 100 seed weight and haulm yield compensate to produce high yield. Increased yield could be a result of these two components. In Table 4.3 (f), there was highly significant (P≤0.01) positive correlation between grain yield and haulm yield. This means that as haulm yield increases, grain yield increases. Number of pods per plant was negatively correlated with 100 seed weight. Similar results were also obtained in a previous study of bambara groundnut by Ofori (1996).

4.2.2 Linear correlation for a combined data

The number of pods per plant is the yield component that is determined first, whereas seed weight is the last component to be determined during the development of the plant. Table 4.4 indicated the correlation matrix results for yield and yield components of the bambara genotypes across six localities. Ayaz *et al.* (2001) and Diepenbrock (2000) reported that a negative relationship could occur between number of pods per plant and 100 seed weight in grain legumes. The findings of this study are in contrast with the reports by these authors.

Grain yield correlated positively with nearly all the measured traits except for 50% flowering and days to maturity (Table 4.4). The positive relationship between grain yield and 100 seed weight puts more emphasis on the importance of planting large seeded genotypes of bambara groundnut. Manoharan *et al.*

(1990) reported that pod yield was positively correlated with pods per plant, and dry matter accumulation.

Authors have shown that the number of pods per plant was strongly positively correlated with seed yield (Withers, 1982). The current study supports these findings, because the number of pods per plant was positively correlated with grain yield. Haulm yield was stronger correlated with grain yield when compared to other traits. Haulm yield showed highly significant ($P \leq 0.01$) positive correlation with 100 seed weight, number of pods per plant and root weight, with 100 seed weight showing stronger positive correlation than the number of pods per plant and root weight. This strong correlation indicates the potential partitioning of photosynthates into reproductive organs relative to vegetative organs. Hundred seed weight showed a weak positive correlation with pods per plant and root weight, while the number of pods per plant had a weak positive correlation with root weight.

Table 4.3(a) Simple linear correlations of seven characters evaluated at Loc1.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	0.4798*					
HSW	0.4356*	-0.1507				
P/PLT	-0.0476	-0.1301	-0.3288			
RW	0.2481	0.0658	0.3070	0.0969		
50%DFLW	-0.1773	0.1536	-0.1959	0.1805	-0.1328	
DM	-0.1262	-0.0128	0.3446	-0.3138	-0.1351	-0.0877

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; *p ≤ 0.05

Table 4.3(b) Simple linear correlations of seven characters evaluated at Loc2.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	-0.2044					
HSW	0.5537*	-0.1014				
P/PLT	0.2905	0.1922	0.1288			
RW	0.0850	0.2552	-0.2634	0.4518*		
50%DFLW	-0.0459	-0.2051	-0.0020	-0.4541*	-0.3511	
DM	-0.1616	-0.4205*	-0.0063	-0.5190*	-0.3592	0.3899

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; *p ≤ 0.05

Table 4.3(c) Simple linear correlations of seven characters evaluated at Loc3.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	-0.0128					
HSW	0.1612	0.1449				
P/PLT	-0.0275	-0.2366	-0.4401*			
RW	-0.2895	0.1556	0.1079	-0.1903		
50%DFLW	-0.0565	-0.0353	-0.1944	0.1236	-0.4553*	
DM	0.1523	0.3221	0.1263	-0.2093	-0.4700*	0.3178

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; *p ≤ 0.05

Table 4.3(d) Simple linear correlations of seven characters evaluated at Loc4.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	-0.1003					
HSW	0.3937	-0.0941				
P/PLT	-0.1511	0.1171	0.2551			
RW	-0.1641	-0.0357	-0.0007	0.5270**		
50%DFLW	-0.3216	-0.2081	-0.2639	-0.1711	-0.2061	
DM	0.0628	0.1196	0.2635	-0.1389	-0.0323	0.0348

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; ** p ≤ 0.01

Table 4.3(e) Simple linear correlations of seven characters evaluated at Loc5.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	0.5666**					
HSW	0.5888**	0.0581				
P/PLT	0.0142	-0.3791	0.0852			
RW	-0.1489	-0.0840	-0.3388	-0.1013		
50%FLW	-0.2190	-0.1822	-0.0747	0.2311	0.0173	
DM	-0.1195	-0.0724	-0.1942	-0.0101	-0.0640	-0.3985

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; ** p ≤ 0.01

Table 4.3(f) Simple linear correlations of seven characters evaluated at Loc6.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	0.6864**					
HSW	0.1663	0.0398				
P/PLT	-0.2703	-0.3143	-0.1284			
RW	-0.0097	-0.3419	0.0624	0.1661		
50%FLW	0.4359*	0.3546	-0.1913	0.0184	-0.0895	
DM	0.2113	-0.1492	-0.1989	0.3147	0.4361*	0.1395

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; *p ≤ 0.05, ** p ≤ 0.01

Table 4.4 Combined linear correlations for seven traits of bambara groundnuts across six environments.

Characters	Grain Yield (kg/ha)	Haulm Yield (kg/ha)	100 seedwt (g)	Pods per plant (#)	Root weight (g)	50%Days to flower
HY	0.7321**					
HSW	0.6407**	0.4884**				
P/PLT	0.3425**	0.2947**	0.2731**			
RW	0.3020**	0.3091**	0.2177**	0.3115**		
50%DFLW	-0.1508	-0.1266	-0.1788*	-0.0704	-0.2403**	
DM	-0.0400	-0.0748	-0.0365	-0.1513	-0.0862	0.0618

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; P/PLT = pods per plant; RW = root weight; FLW = flowering; DM = days to maturity; *p ≤ 0.05, ** p ≤ 0.01

4.3 Combined analyses for the two planting dates

The data of the two planting dates were analyzed (Table 4.5) and it was shown that there were no significant differences between the planting dates for yield and yield components, except for days to maturity. There was also no significant planting date with genotype interaction for yield. For this reason it was decided to do all further analyses on the six environments, and not to separate them according to planting date.

Table 4.5 Mean squares for the combined analyses of variance for characters as influenced by planting date and genotype.

Source of Variance	Mean squares					
	Grain yield	Haulm yield	100 seed wt	Number of pods/plant	Days to 50% flower	Days to maturity
Plant date	41854.3	8634	0.840278	5160.0278	19.9910714	1267.603**
Genotype	3604742**	17700147**	119.554563	6219.6825**	22.5625000	890.028**
P x G	289190.7	17040647**	63.524802*	6902.1230*	69.4990079	104.790**

*p ≤ 0.05, ** p ≤ 0.01

4.4 Combined analysis of variance across six localities

In order to develop genotypes that are more stable, better understanding of the contribution of the genotypes, environment and their interaction as a source of variation is very important. Table 4.6 summarized the mean squares relevant to the study of genotype by environment interactions (gxe) from a pooled analysis of variance. The results from the combined analyses showed highly significant (P≤0.01) mean square values for locations, genotypes and gxe. This is an indication of the large differential responses of genotypes to environments, across the six localities for nearly all the traits. There were no significant differences between the blocks, which mean that the field trials were homogenous between the blocks. Genotype effects were significantly (P≤0.05) different for only the number of pods per plant, while for the remaining measured traits both the genotype and gxe were highly significant (P≤0.01). Since the interaction between genotype and environment is significant, it could be attributed to the different reaction of the genotypes to environments or due to differences between the environments. Environment had a larger role to play than both genotype and gxe in determining yield and yield components by contributing 62% of the total variation, thus complicating selection of genotypes. This was an indication of the need for conducting stability analysis.

The partitioning of sum of squares of components to determine percentage of contribution of each treatment for all traits measured on the genotypes are indicated in Table 4.7 together with means of the traits across the environments. SB4-4's performance was the best across locations with the highest grain yield of 2451kg/ha. The means varied greatly from 2451 (SB4-4) to 1075kg/ha (SB16-5A) and had an average of 1605kg/ha. For haulm yield SB8-1 gave the highest value, which did not significantly differ from SB20-2A and SB1-1 ranking second and third respectively. SB8-1 performed significantly higher than SB9-1, SB16-5A, and SB7-1. For 100 seed weight, SB1-1 had the highest value, followed by SB4-4 and SB19-3 respectively. The smallest seed weight was obtained by

SB20-2A, SB16-5A and SB9-1. The average was 45g and the range from 42.8 to 50.6g. SB20-2A had the most pods per plant and it was not significantly higher than SB9-1 (second best). SB20-2A performed significantly better than SB1-1, SB4-4, SB19-3, and SB8-1. The rankings of the genotypes were not constant over locations for yield and yield components.

Table 4.6 Mean squares of block, environment, genotype and gxe for four characteristics in a combined analysis of variance.

Source of Variation	Grain yield (kg/ha)	Haulm yield (kg/ha)	100 seed weight (g)	Number of pods/plant
Block	98486.4	2701196.9	30.9	2626.7
Genotype	3604742.0**	17700147.5**	119.5**	6219.7*
Environment/Loc	22945210.2**	205785536.4**	604.6**	43668.6**
Gxe interaction	8748491.1**	8413867.9**	41.3**	7128.1**
C.V.	24.79	25.11	9.32	31.86

*p ≤0.05, ** p ≤0.01

Table 4.7 Mean yields, LSD's and CV's and the ranks of four characteristics of the bambara groundnut genotypes across six localities.

Genotype	GY (kg/ha)	R	HY (kg/ha)	R	HSW (g)	R	Pods per plt	R
SB1-1	1973	2	7313	3	50.6	1	167	5
SB4-4	2451	1	6520	5	46.2	2	154	6
SB7-1	1541	5	5005	8	43.8	5	182	3
SB8-1	1419	6	7483	1	44.1	4	146	8
SB9-1	1137	7	5599	6	42.8	8	190	2
SB19-3	1699	3	6734	4	44.4	3	149	7
SB16-5A	1075	8	5352	7	43.1	7	175	4
SB20-2A	1545	4	7435	2	43.4	6	193	1
Mean	1605		6430		44.8		170	
$LSD_{(0.05)}$	221		895		2.3		29	
%Contribution G	13.6		7.3		11.7		5.5	
%Contribution E	61.9		60.5		42.3		27.7	
%Contribution Gxe	16.5		17.3		20.3		31.7	

GY = grain yield; HY = haulm yield; HSW = 100 seed weight; No. of p/plt = number of pods per plant

4.5 Stability analysis

Four stability analyses were conducted. The conventional regression model (Eberhart & Russell, 1966), Cultivar superiority measure (Lin & Binns, 1988), Wricke's ecovalence (Wricke, 1962) and the AMMI model (Gauch & Zobel, 1996).

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4.5.1 Eberhart and Russell's joint regression analysis

This stability analysis is the most widely used and published statistical procedure in plant breeding for providing the genotypic stability. The model uses joint linear regression where the mean yield of each genotype over six testing sites is regressed on the environmental mean. Table 4.8 presents the pooled analysis of variance for the four traits of the eight bambara genotypes. The model partitions the sum of squares due to the environments and genotype x environment, into environment (E) linear, genotype x environment (gxe) linear and deviation from the regression model (non-linear). The result showed highly significant ($P \leq 0.01$) differences between the genotypes for grain yield and 100 seed weight and a significant ($P \leq 0.05$) difference for haulm yield. Number of pods per plant showed no significant differences for all the variance components while haulm yield showed no differences for gxe. Gxe (linear) was highly significant ($P \leq 0.01$) and significant ($P \leq 0.05$) for grain yield and 100 seed weight, respectively. This suggests that the ranking of the genotypes was not constant. Similar findings about the significance of gxe have been reported by Khan *et al.* (1988) in chickpea and Ali *et al.* (2001) in groundnut. The gxe's (linear) sum of squares was not as large a portion of the gxe when compared with environment (linear) sum of squares and residual sum of squares for the measured characteristics.

Eberhart & Russell (1966) and Finlay & Wilkinson (1963) described stability of a genotype in different manners. Finlay & Wilkinson regarded a stable genotype to

have an average b-value of zero, while Eberhart & Russell said a stable cultivar must have a b-value of one. Overall Eberhart & Russell explained a stable genotype to have a high mean yield, regression coefficient (b) of one and deviation from regression (S^2d) of close to zero. They regarded b-value to be a measure of the genotype's performance, and S^2d as a measure of stability. The regression coefficient and deviation from regression for four traits of bambara genotypes are given in Table 4.9. For grain yield, when mean yield, b-value and S^2d are considered together, the most stable genotype was SB19-3, since it had an average grain yield of 1699 kg/ha (ranking third), b = 1.0471 close to one and S^2d = 40170 (ranking third). The regression deviation was also low for SB16-5A and SB20-2A. The slopes of SB1-1 and SB4-4 were higher ($P \leq 0.01$) than one. SB1-1 and SB4-4 were unstable genotypes with the highest S^2d value, and b value greater than 1 but with good average yield.

With regard to haulm yield SB19-3, SB16-5A, SB8-1, and SB20-2A showed the best stability. SB8-1 is regarded as the most stable genotype, when mean yield of 7483 kg/ha, regression coefficient of 1.376 and deviation from regression of -29276 are taken into account. The slope of SB1-1 and SB4-4 was higher ($P \leq 0.01$) than one while those of SB7-1 and SB9-1 were significantly ($P \leq 0.05$) less or equal to one.

The most stable genotypes for 100 seed weight were SB20-2A, SB1-1 and SB4-4 because they had an S^2d value that was close to zero. SB8-1, SB16-5A, and SB9-1 had S^2d values larger than zero. SB1-1 and SB4-4 were the two genotypes with the best stability when taking into consideration the mean yield, regression coefficient and deviation from regression. For 100 seed weight, the slope of SB8-1 and SB16-5A were significantly higher than one ($P \leq 0.05$).

For the number of pods per plant SB19-3, SB4-4, and SB8-1 showed good stability because of their smaller S^2d value, which is closer to zero. SB20-2A had S^2d greater than zero, with the largest number of pods per plant and a b value

smaller than one. When taking all characters into consideration SB19-3 and SB20-2A seemed to be the most stable genotypes. Overall the stability parameters varied greatly from one character to another. The slope of SB1-1 and SB20-2A were significantly lower ($P \leq 0.05$) than one.

Tables 4.8 Combined analysis of variance for linear regressions of genotype mean on the environmental mean for four parameters during 2004 to 2005 season.

Source of variation	Grain yield			Haulm yield		100 Seed wt		Pods/plant	
	df	SS	MS	SS	MS	SS	MS	SS	MS
Total	143	56859653.85		482438108.5		1769.28		170454.79	
Varieties	7	8411065.212	1201580.74**	41300358.4	5900051.2*	278.94	39.849**	14512.62	2073.23
Env.+ in Var.x Env.	40	48448588.64	1211214.71	441137750.1	11028443.8	1490.34	37.258	155942.17	3898.55
Env. in linear	1	38242017.88		342975922.6		1007.76		72781.09	
Var. x Env. (linear)	7	5021002.21	717286.03**	29153921.0	4164845.9	178.61	25.515*	14291.54	2041.65
Pooled deviation	32	5185568.54	162049.02	69007906.5	2156497.1	303.97	9.499	68869.54	2152.17
Residual	96	4827927.55	50290.91	83817512.18	873099.09	611.79	6.373	92038.89	958.74
C.V. %		24.20		25.17		9.76%		31.66%	
R-squared		0.8930		0.8436		0.7960		0.5584	

*p ≤ 0.05, **p ≤ 0.01

Table 4.9 Stability parameters of the eight bambara groundnut genotypes for four traits at six locations.

VARIETY	Grain yield		Haulm yield		100seedwt		Pods/plant	
	b	S^2d	b	S^2d	b	S^2d	b	S^2d
SB1-1	1.4216	211103.4765	1.4528	3066157.3109	0.9090	0.4624	0.3633	1603.4601
SB4-4	1.6181	411786.2267	1.2168	2345565.5241	0.7260	-3.5444	0.9378	-224.9513
SB7-1	1.0734	51925.8071	0.9578	1832929.4198	0.4632	3.1880	1.1494	570.7377
SB8-1	0.9968	112641.7055	1.3760	-29276.2940	1.2705	12.4442	1.4148	328.0100
SB9-1	0.6185	54288.3565	0.9035	1721017.5345	1.1367	5.4721	1.6817	1868.7298
SB19-3	1.0471	40170.7033	0.6688	4406.3489	0.4693	-4.1759	1.1458	-210.3291
SB16-5A	0.7477	-19677.4441	0.7051	284399.4928	1.7841	11.9155	1.0008	3287.9567
SB20-2A	0.4768	31826.0087	0.7192	1041984.6183	1.2412	-0.7510	0.3063	2323.8632

4.5.2 Lin and Binns cultivar superiority measure (Pi) analysis

The superiority measure (Pi) of cultivars is estimated by the squares of differences between an entry mean and maximum entry mean, summed and divided by twice the number of locations (Lin & Binns, 1988). These authors indicated that cultivars with low or small Pi value are considered to be the more stable ones. A summary of the cultivar superiority measure (Pi) for four traits of bambara groundnut genotypes is shown in Table 4.10.

According to the authors' superiority measure method, SB4-4 was the most stable genotype with regards to grain yield, followed by SB1-1 and SB19-3. This correlates very well with the average yield rankings (Table 4.7). SB20-2A, SB16-5A and SB9-1 were unstable genotypes. In terms of haulm yield, SB1-1, SB8-1 and SB20-2A were regarded as the most stable genotypes with SB16-5A, SB9-1 and SB7-1 being the unstable genotypes. The cultivar superiority measure for 100 seed weight indicates that SB1-1, SB4-4, and SB19-3 had the best stability. SB7-1, SB9-1, and, SB16-5A were the unstable genotypes. With regards to the number of pods per plant SB20-2A, SB9-1, SB7-1 and SB16-5A, which were the unstable genotypes for all characteristics, were found to be the most stable genotypes. The most stable genotypes for all traits were found to be unstable for number of pods per plant. In most cases there was good similarity between mean yield ranking and the superiority rankings measures.

Table 4.10 Lin and Binns' cultivar superiority measure (Pi) and their ranks (R) of four traits measured of eight bambara groundnut genotypes across six environments.

Cultivar superiority								
Genotype	Grain yield	R	Haulm yield	R	HSW	R	Pods/plant	R
SB1-1	314498.30	2	3072273.89	2	1.56	1	6099.99	6
SB4-4	64954.82	1	4571330.22	4	15.22	2	5385.96	5
SB7-1	852931.23	4	9314894.63	8	35.62	6	4303.92	3
SB8-1	1075744.77	5	1630928.12	1	34.76	5	7632.61	8
SB9-1	1661017.72	8	8196581.19	6	45.29	7	3448.88	2
SB19-3	716831.15	3	4605228.48	5	28.19	3	7018.42	7
SB16-5A	1590888.80	7	8749525.49	7	48.06	8	4747.72	4
SB20-2A	1100834.27	6	3306613.26	3	34.56	4	2846.74	1

HSW = 100 seed weight

4.5.3 Wricke's Ecovalence (Wi) analysis

The ecovalence (Wi) or the stability of the i^{th} genotype is its interaction with environments, squared and summed across environments. The genotype with the lowest ecovalence has less fluctuation across the environments and therefore it is considered to be more stable than the others.

Wricke's ecovalence was determined for four characteristics of the eight bambara groundnut genotypes at six locations during the 2004-2005 growing season (Table 4.11). SB19-3 and SB16-5A were the most stable genotype with regards to grain yield and haulm yield. The unstable genotypes for the two characters were SB20-2A, SB1-1 and SB4-4. For 100 seed weight SB4-4, SB1-1 and SB20-2A showed good stability. SB16-5A had the highest ecovalence value between the genotypes and was therefore regarded as the least stable genotype. For number of pods per plant, SB4-4 had the smallest ecovalence value and was selected as the most stable genotype, with SB16-5A and SB20-2A being regarded as the least stable genotypes.

Table 4.11 Wricke's ecovalence and ranks (R) for four characteristics of bambara groundnut genotypes tested in six environments during 2004-2005.

Ecovalence (W_i)								
Genotype	Grain yield	R	Haulm yield	R	HSW	R	Pods/plant	R
SB1-1	1895334.65	7	24546904.63	8	28.38	2	13936.80	5
SB4-4	3674472.33	8	14889299.32	7	20.77	1	2970.37	1
SB7-1	434635.24	3	10900474.34	5	74.54	6	6320.97	3
SB8-1	651779.28	4	9437647.07	3	84.48	7	6712.41	4
SB9-1	1114118.01	5	10775928.66	4	49.73	5	15538.19	6
SB19-3	372444.75	1	8213373.32	1	44.26	4	3187.14	2
SB16-5A	426667.70	2	8357374.70	2	150.59	8	16986.79	7
SB20-2A	1637118.77	6	11040825.50	6	29.81	3	17508.42	8

HSW = 100 seed weight

4.5.4 AMMI analysis

The Additive Main Effects and Multiplicative Interaction (AMMI) method integrates the analysis of variance into an unified approach (Gauch, 1988; Gauch & Zobel, 1996). The IPCA scores of a genotype in the analysis are an indication of the stability of a genotype over the environments (Gauch & Zobel, 1997).

The combined analysis of variance (ANOVA) of eight genotypes at six locations according to AMMI model 2 is shown in Table 4.12. The ANOVA showed highly significant (P≤0.01) differences between environments, genotypes and most importantly for the genotype by environment interaction (gxe) for traits measured, while indicating no significant differences between genotypes for haulm yield and pods per plant. The IPCA1 axis was highly significant (P≤0.01) for grain yield, while IPCA2 and IPCA3 axes were significant at P≤0.05. IPCA1 and IPCA2 axes explained 71% and 12% of the total gxe, while the remaining 17% was shared between the other IPCA's. With regards to haulm yield, IPCA1 and IPCA2 axes explained 83% of the gxe sum of squares, with the remaining 17% shared between the other IPCA's. This showed that AMMI model 2 was best suited for this data set. IPCA1 and IPCA2 axes for 100 seed weight explained 81% of the gxe. The remaining IPCA's contributed 19% to the gxe, which was shared by the other IPCA's. The IPCA1 and IPCA2 axes were highly significant (P≤0.01) and significant (P≤0.05) respectively. For number of pods per plant, IPCA1, IPCA2, and IPCA3 axes were highly significant and explained 93% of the gxe sum of squares with only 7% being shared between the remaining IPCA's. The AMMI model 2 was used because it gave the best fit for the whole data set. The first IPCA was also able to remove most of the noise from the data.

The greater the IPCA scores (-ve or +ve), the more specifically adapted a genotype is to a certain environment. The closer the IPCA scores to zero, the more stable the genotypes over the tested locations. Table 4.13 indicates the AMMI 2 model IPCA1 and IPCA2 scores and ASV of four characteristics for eight

genotypes. For to grain yield SB7-1, followed by SB19-3 and SB8-1 were the most stable genotypes when IPCA1 score is taken into account. In contrast SB1-1 and SB4-4 were adapted to specific environments, where they had the top yields, respectively. However, IPCA2 score regarded genotypes SB20-2A and SB8-1 to be unstable. According to Purchase (1997) the AMMI Stability Value (ASV) is able to give a balanced measurement between the two IPCA scores. The ASV comes into play when the two IPCA scores are different, in order to give a balanced measurement between the two IPCA's. It indicated that SB7-1 is the most stable genotype, followed by SB9-1, SB19-3 and SB8-1. For haulm yield, the IPCA1 score found SB8-1, SB7-1 and SB9-1 to be the most stable genotypes; and SB1-1, SB4-4 and SB20-2A unstable genotypes. IPCA2 score disagrees with the findings with regard to SB1-1 and SB16-5A being stable genotypes, and SB7-1, SB8-1 and SB9-1 unstable. The ASV value was in agreement with IPCA1 scores. For 100 seed weight IPCA1 scores indicated that SB8-1, followed by SB4-4 and SB1-1 are the most stable genotypes respectively. The IPCA2 scores found SB19-3, SB16-5A and SB20-2A to be the stable genotypes, while ASV regarded SB4-4, SB1-1 and SB20-2A to be the more stable genotypes. ASV and IPCA 1 score also agreed that the unstable genotypes were SB19-3, SB7-1 and SB16-5A. The IPCA 1 scores were in line with ASV when determining the stable genotypes. The most stable genotypes were SB19-3 followed by SB4-4 and SB7-1. SB20-2A was adapted to specific environments and gave the highest pod number per plant.

The AMMI model summarizes patterns and relationships of genotypes and environments successfully. Figure 4.1 shows the AMMI model 2 biplot of grain yield for six locations. The IPCA2 scores also play a major role in the gxe (Purchase, 1997), so they should be plotted against the IPCA1 scores to further explore the adaptations. Genotypes closer to zero or center of the figure are more stable. Figure 4.2 indicates the IPCA1 vs IPCA2 score for grain yield to further explore the adaptations. The further away from zero the IPCA score for the environments is, the more interaction the environment has with the

genotypes, thus making it difficult to choose genotypes for that environment. There was less variation between the environments. Four locations were clustered in the lower potential environments quadrants. The lower yielding environments were Loc1(A), Loc4(D), Loc5(E) and Loc2(B), which are clustered in quadrant I and IV respectively. Loc3(C) and Loc6(F), which were under irrigation, clustered in the higher yielding environments in quadrant III. Most of the genotypes were plotted on an average yield of 1605 kg/ha. SB1-1 was adapted to higher potential environments in quadrant III. On the other hand SB7-1 was the most stable genotype. AMMI biplot IPCA1 vs IPCA2 showed that SB4-4, SB20-2A, SB8-1 and SB1-1 are outliers (unstable) and thus more interactive with environments. SB7-1 and SB19-3 were close to zero and more stable (Figure 4.2).

In Figure 4.3 the IPCA 1 scores for both the genotypes (small case) and the environments (upper case) were plotted against the mean haulm yield for genotypes and environments respectively. By plotting both the genotype and the environment on the same graph, the relationship between the genotypes and environments can be seen clearly. There was variation between the environments. They were spread from lower yielding environments in quadrants I and IV to higher yielding environments in quadrants II and III. The high yielding environments were both Loc3(C) and Loc6(F) in quadrant II and III. This was expected since the localities were irrigated during the growing season. Loc1 (A), Loc4(D) and Loc2(B) were the lower yielding environments. SB7-1 and SB8-1 were genotypes that are closer to zero and thus considered stable. It was difficult to select the most stable genotypes. Most of the genotypes were shown to be more interactive with environments because they are far from the centre. SB9-1 was the one that is closest to the centre and zero and thus the more stable genotype (Figure 4.4).

In Figure 4.5, the environments are clustered in quadrant I, which is a lower yielding environment. The higher potential environments namely Loc3(C) and

Loc6(F) are all in quadrant III as expected. The stable genotypes were SB8-1, SB4-4 and SB1-1. SB4-4 and SB20-2A were more stable when plotting the IPCA 1 and IPCA 2 scores. The IPCA score for the environments were further away from zero. Most of the genotypes were more interactive with the environment, thus making it difficult to choose genotypes for that environment (Figure 4.6).

For the number of pods per plant, Figure 4.7 indicates that Loc6(F) and Loc4(D) seemed to have the lowest interaction with the genotypes. Loc3(C) and Loc6(F) were under irrigation and they fell in quadrant III. The lower potential environments were Loc1 and Loc4 (A and D) and Loc2 and Loc5 (B and E). This may have been so since Taung (B and E) received less rain in the first stages of growth and while Potchefstroom (A and D) trial was planted on clay soil and received more rainfall during early stages of growth, which caused waterlogging in the plots. SB19-3 was the most stable genotype. Figure 4.8 shows that SB7-1 is close to the center when compared to the other genotypes, thus less interactive with environment and considered stable.

Table 4.12 Combined ANOVA for eight bambara groundnut genotypes for four traits at six locations using the AMMI model.

Source	Grain yield			Haulm yield		Hundred seed weight		Number of pods/plant	
	df	SS	MS	SS	MS	SS	MS	SS	MS
Total	143	185062744.2		1698766862.2		7143.170		787481.026	
Environments	5	114726053.7	22945210.7**	1028927767.7	205785553.5**	3023.287	604.657**	218343.259	43668.652 **
R within Env.	12	1181837.2	98486.4	32414360.5	2701196.7	370.836	30.903	31520.002	2626.667
Genotype (G)	7	25233195.6	3604742.2**	123901075.3	17700153.6*	836.824	119.546**	43537.867	6219.695
G x Env.	35	30619712.3	874848.9**	294485482.6	8413870.9**	1447.726	41.364**	249483.238	7128.093**
IPCA 1	11	21872192.7	1988381.2**	198156327.6	18014211.6**	781.210	71.019**	98076.418	8916.038**
IPCA 2	9	3534932.8	392770.3*	46191224.7	5132358.3*	391.714	43.524**	71260.043	7917.783**
IPCA3	7	3097276.1	442468.0*	27742005.2	3963143.6	179.561	25.652	62810.811	8972.973**
IPCA4	5	1643865.4	328773.1	21041287.2	4208257.4	83.375	16.675	16418.027	3283.605
IPCA5	3	471445.3	157148.4	1354637.9	451546.0	11.865	3.955	917.939	305.980
Residual	84	13301945.4	158356.49	219038176.0	2607597.3	1464.498	17.435	244596.660	2911.865

R= Reps, * $p \leq 0.05$, ** $p \leq 0.01$

Table 4.13 Rankings (R_1) of mean of four traits, IPCAI 1 and 2 scores, and AMMI stability value (ASV) with its rankings (R_2) for four traits of the eight genotypes.

Entry	Grain yield					Haulm yield					100 Seed weight (g)					Number of pods/plant				
	R_1	IPCA1	IPCA 2	ASV	R_2	R_1	IPCA1	IPCA2	ASV	R_2	R_1	IPCA1	IPCA2	ASV	R_2	R_1	IPCA1	IPCA2	ASV	R_2
SB1-1	2	-23.722	7.9960	146.99	7	3	-54.4578	0.4873	233.62	8	1	-0.5970	-1.2566	1.7	2	5	5.867	5.9798	10.1	7
SB4-4	1	-35.529	-13.947	220.25	8	5	-38.5464	-5.9175	165.47	7	2	0.3399	-0.3886	0.8	1	6	-1.691	-3.5528	4.3	3
SB7-1	5	-0.0721	7.3160	7.33	1	8	-13.1124	46.4673	72.96	2	5	1.7234	-1.3471	3.7	7	3	-2.195	2.5669	4.0	2
SB8-1	6	6.3729	17.501	43.14	4	1	-9.1729	-39.8508	56.01	1	4	0.1525	2.6351	2.7	5	8	-4.295	4.4399	7.4	4
SB9-1	7	17.873	-1.128	10.58	2	6	22.5379	-7.6621	96.99	3	8	0.8775	0.9123	2.0	4	2	-8.309	-3.3911	11.9	8
SB19-3	3	4.9522	8.3921	31.77	3	4	26.6158	4.6993	114.28	4	3	1.4221	-0.1544	2.8	6	7	0.536	3.3065	3.4	1
SB16-5A	8	10.769	-7.8626	67.09	5	7	30.2085	-4.5429	129.67	5	7	-3.0086	-0.1696	6.0	8	4	5.203	-2.0953	7.5	5
SB20-2A	4	19.355	-18.268	121.14	6	2	35.9274	6.3193	154.26	6	6	-0.9097	-0.2312	1.8	3	1	4.885	-7.2538	9.9	6

Table 4.14 Genotypes and environments represented by alphabetic letters in the biplot as illustrated by the AMMI 2 model.

Genotype		Environment	
a	SB1-1	A	Potchefstroom early (Loc1)
b	SB4-4	B	Taung early (Loc2)
c	SB7-1	C	Vaalharts early (Loc3)
d	SB8-1	D	Potchefstroom late (Loc4)
e	SB9-1	E	Taung late (Loc5)
f	SB19-3	F	Vaalharts late (Loc6)
g	SB16-A		
h	SB20-2A		

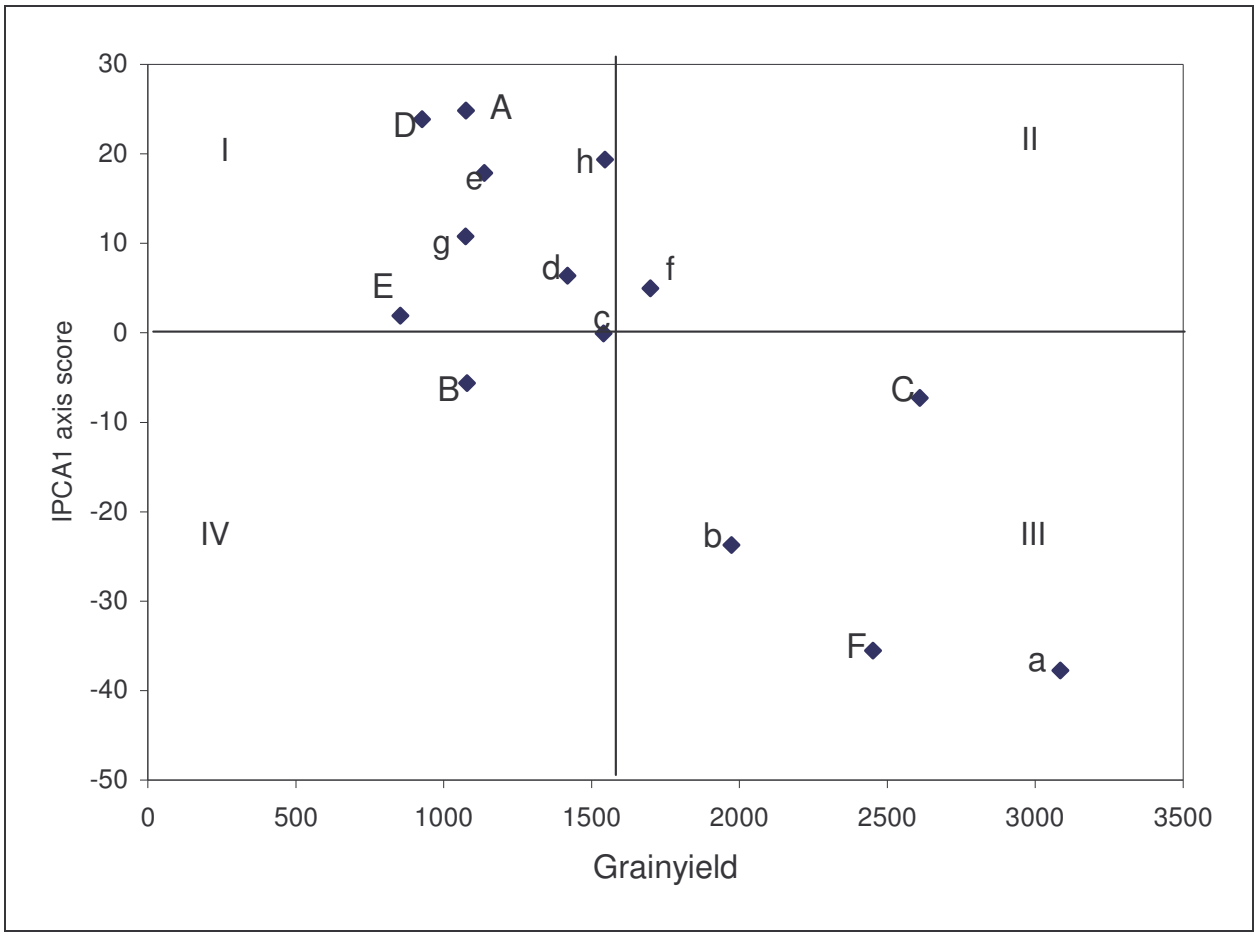

Figure 4.1 IPCA 1 score plotted against yield for genotypes and environments during the 2004 – 2005 growing season for grain yield.

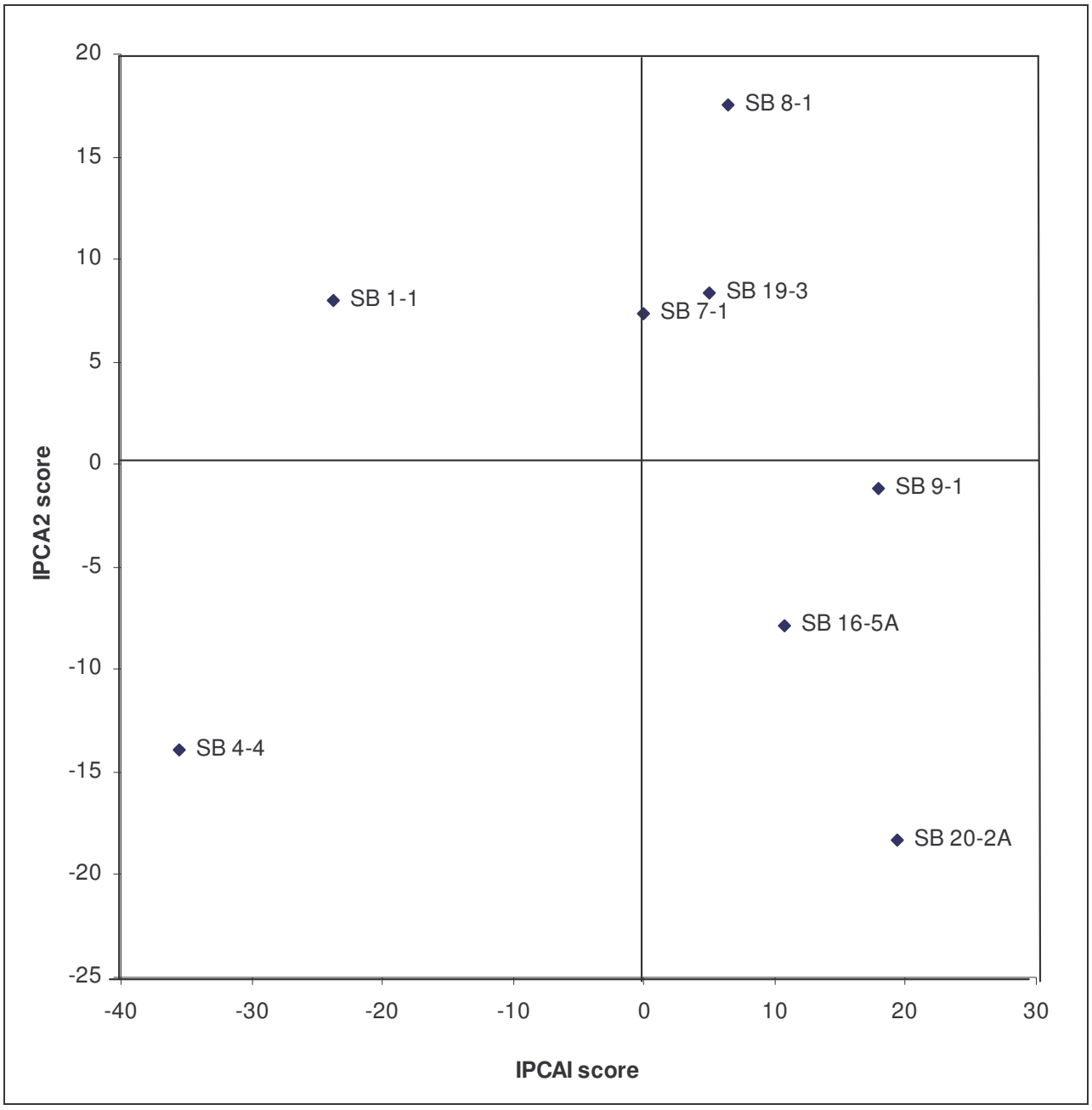

Figure 4.2 Plotted IPCA1 and IPCA2 scores of eight bambara groundnut genotypes tested in six environments for grain yield.

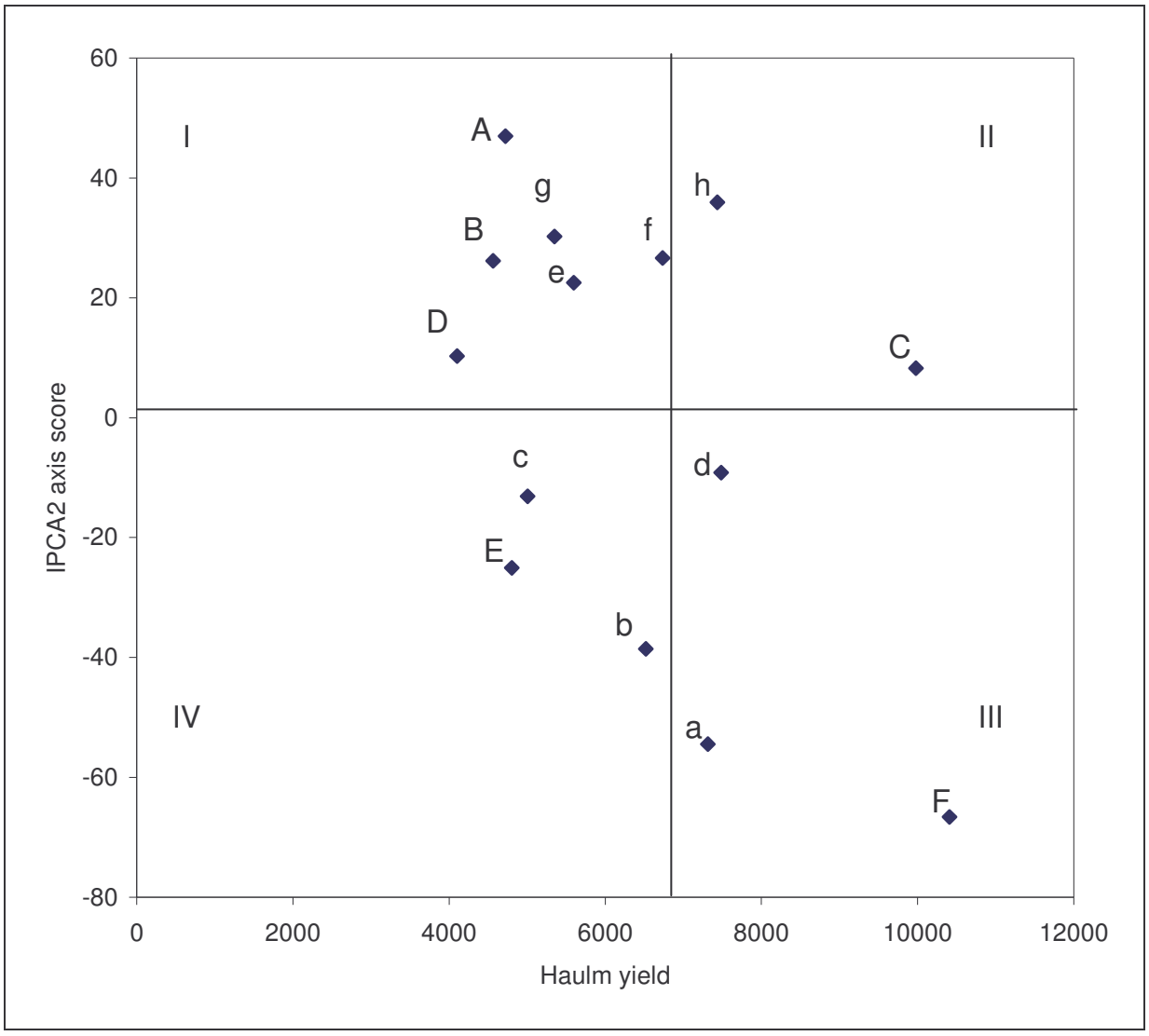

Figure 4.3 IPCA 1 score plotted against yield for genotypes and environments during the 2004 – 2005 growing season for haulm yield.

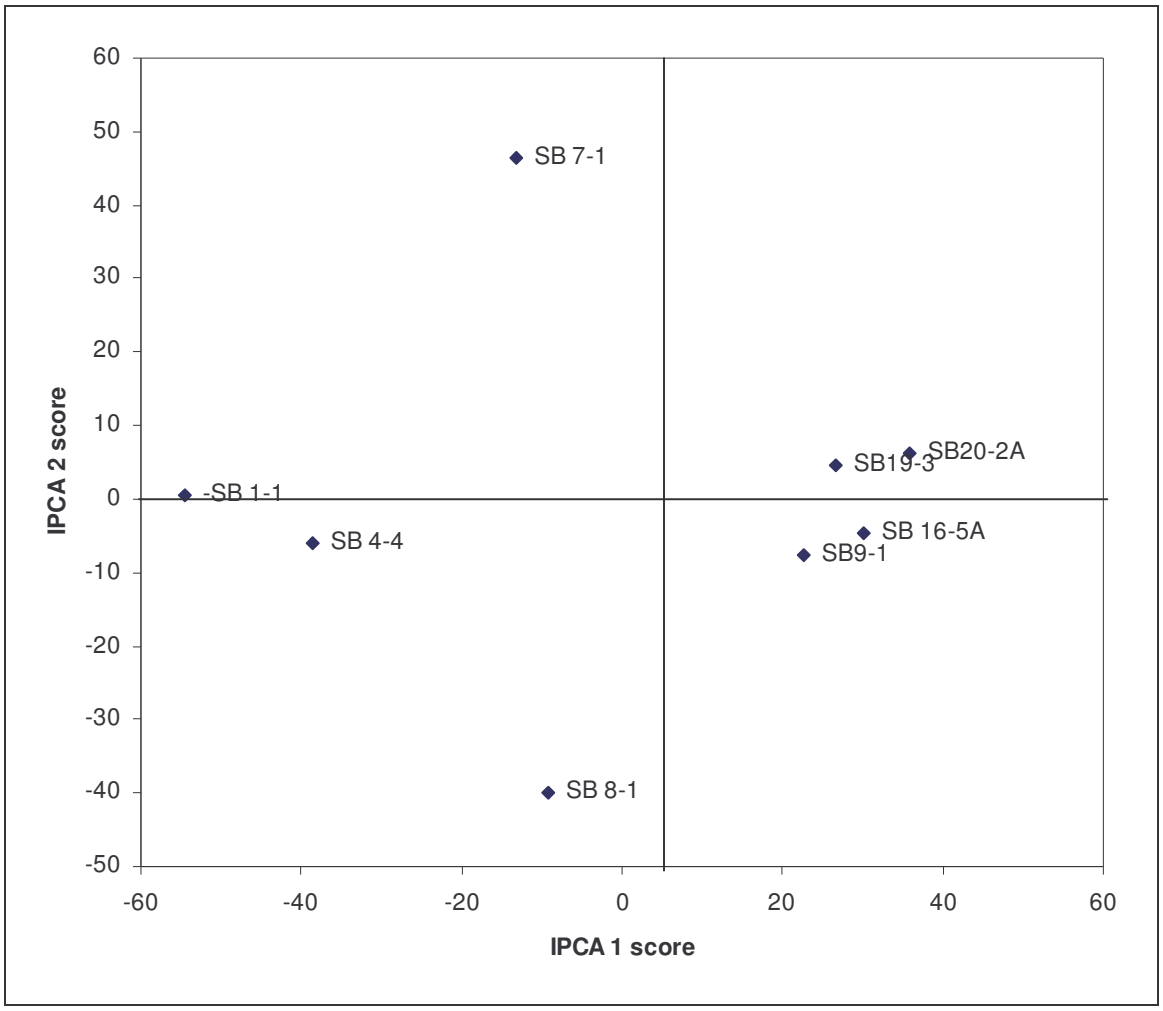

Figure 4.4 Plotted IPCA1 and IPCA2 scores of eight bambara groundnut genotypes tested in six environments for haulm yield.

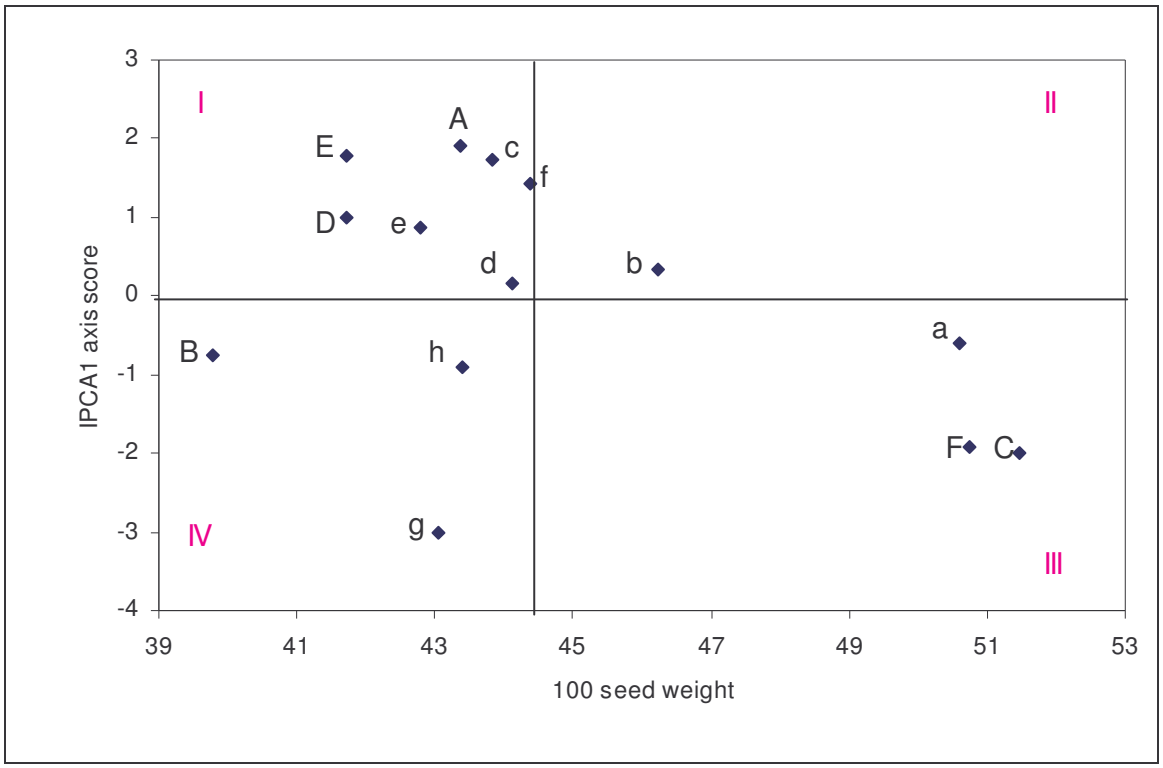

Figure 4.5 IPCA 1 score plotted against yield for genotypes and environments during the 2004 – 2005 growing season for 100 seed weight.

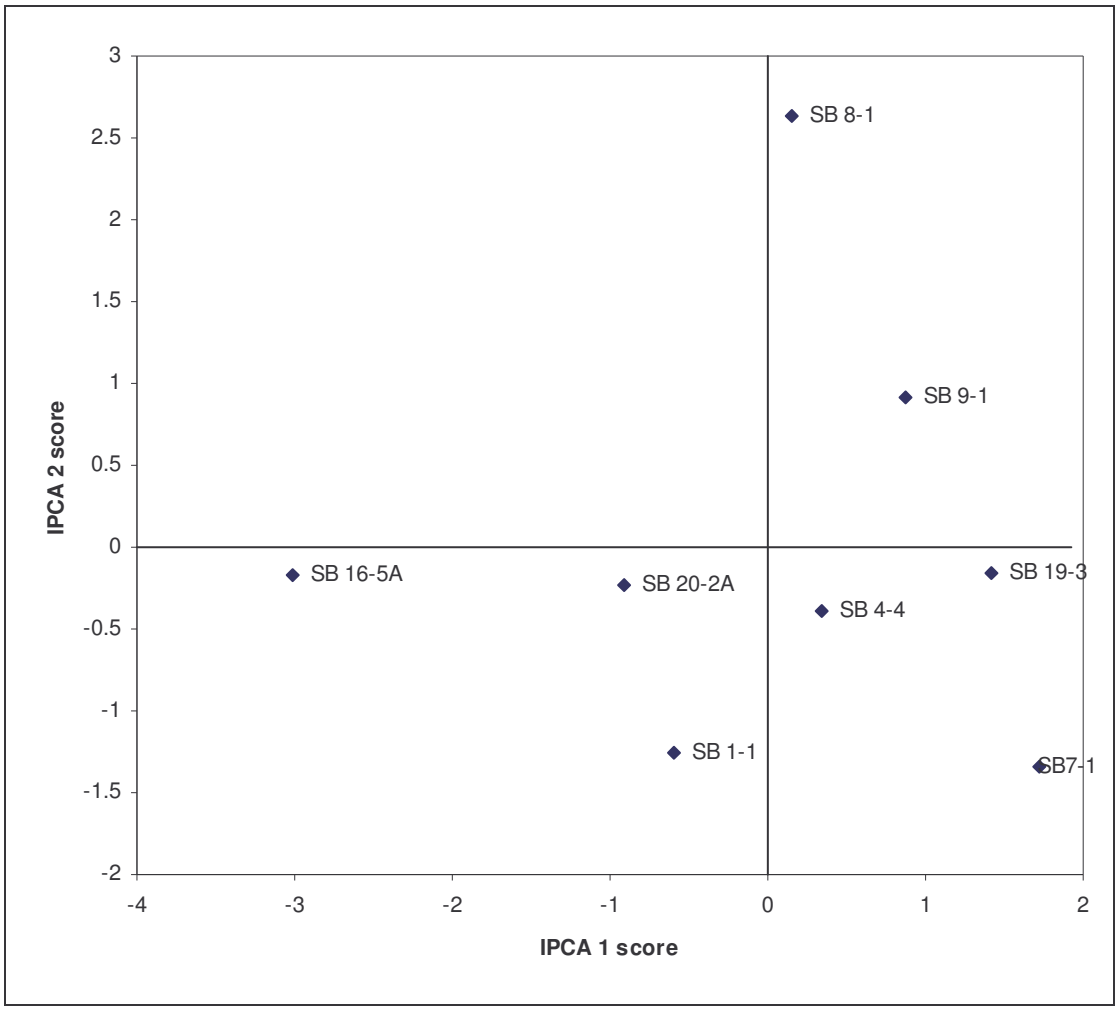

Figure 4.6 Plotted IPCA1 and IPCA2 scores of eight bambara groundnut genotypes tested in six environments for 100 seed weight.

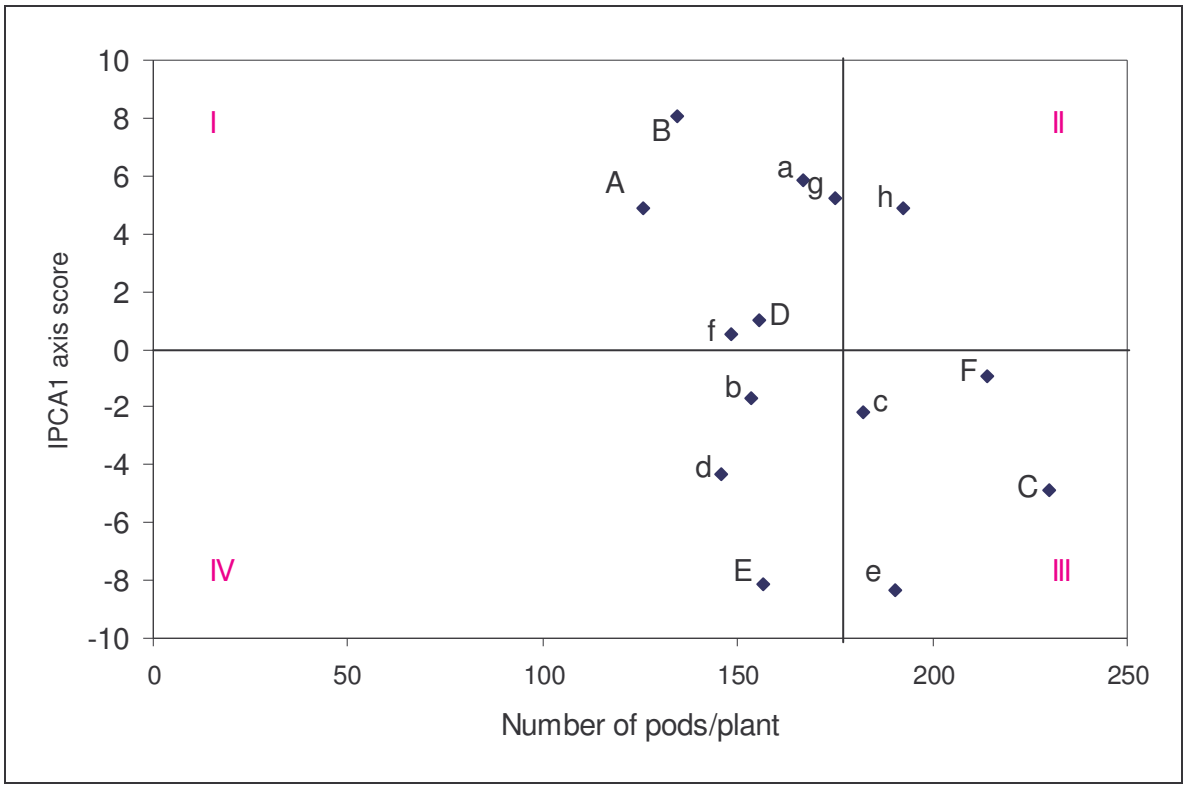

Figure 4.7 IPCA 1 score plotted against yield for genotypes and environments during the 2004 – 2005 growing season regarding number of pods per plant.

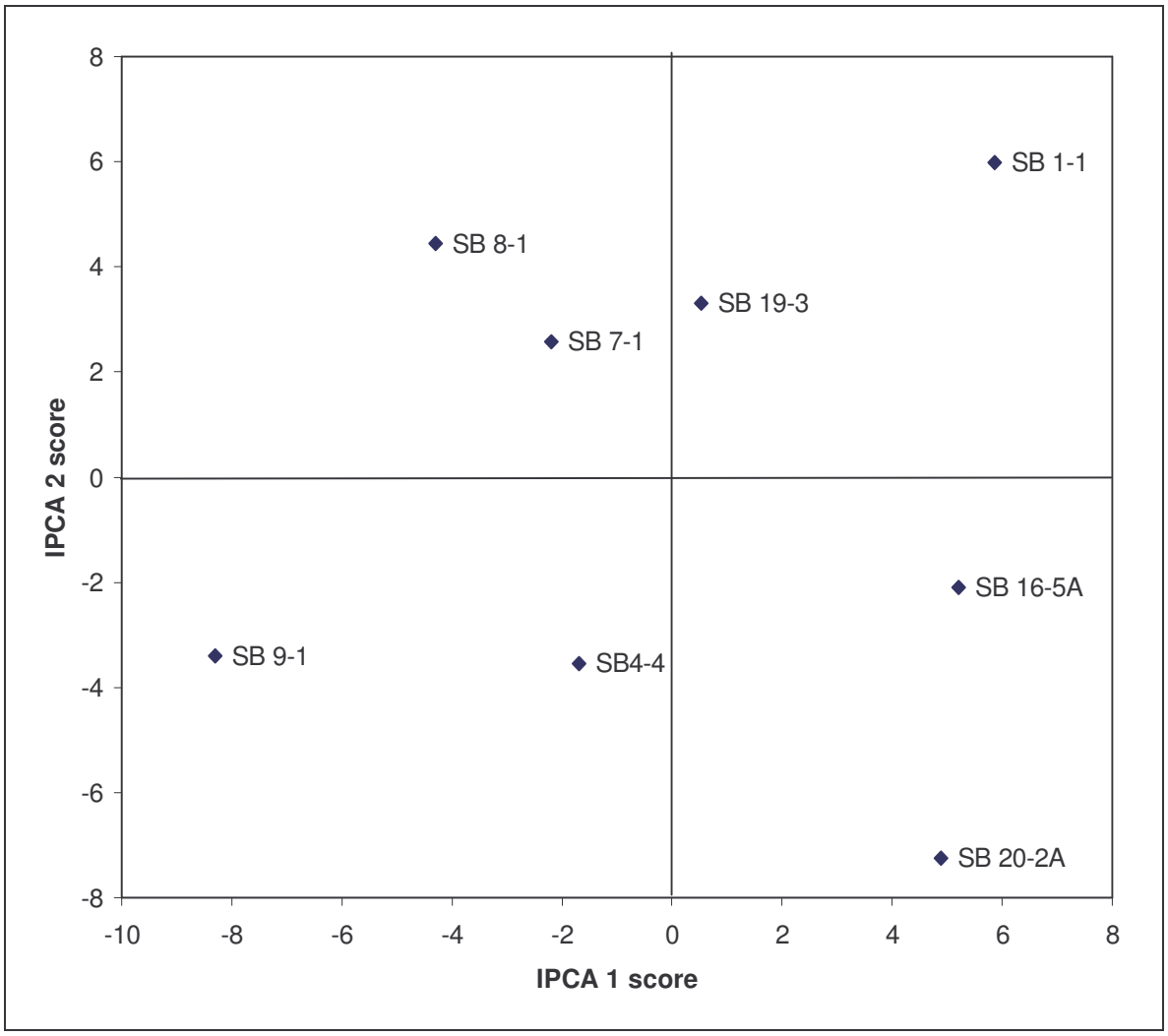

Figure 4.8 Plotted IPCA1 and IPCA2 scores of eight bambara groundnut genotypes tested in six environments for number of pods per plant.

4.6 Comparisons of the stability analyses

Table 4.15 shows the summary of four stability parameters employed to analyze the yield and yield components performance of eight bambara groundnut genotypes evaluated at six locations. The overall mean yield was included in the table to support the stability parameters.

Lin & Binns' (1988) cultivar superiority was similar to the mean yield of a combined ANOVA in determining the most stable genotypes for all the measured traits. The most stable genotype was SB4-4 for grain yield, SB8-1 for haulm yield, SB1-1 for 100 seed weight and SB20-2A for number of pods per plant. SB19-3 was the third most stable genotype from Eberhart and Russell's (1966) regression analysis, cultivar superiority, ASV and combined ANOVA for grain yield.

Wricke's (1962) ecovalance value was similar to Eberhart and Russell's stability in selecting the most stable genotypes (SB16-5A and SB19-3) for almost all characteristics measured, and similar with ASV (SB19-3 and SB7-1). With regards to grain yield, SB7-1 and SB19-3 ranked first and third by ASV and third and first respectively by Wricke's ecovalence value. ASV and Wricke ecovalence value ranked SB4-4 and SB1-1 to be the first and second most stable genotypes for 100 seed weight, while ranking SB19-3 first and second respectively with regards to number of pods per plant. Therefore ASV was similar to Wricke's ecovalence value.

For grain yield SB8-1 was less stable when comparing the stability measure for the three most stable genotypes. The less stable genotype was SB9-1 for haulm yield, because it appeared in one stability parameter and ranked third. SB19-3 was less stable for 100 seed weight. For number of pods per plant, SB8-1 was considered by only Eberhart & Russell to be a stable genotype. The stability parameters were not constant in determining the best genotypes. Lin & Binns's

cultivar superiority and combined ANOVA for mean yields was consistent in determining the most stable genotypes.

Table 4.15 Four stability parameters for average yield of bambara groundnut genotypes across six locations.

Stability Parameter	R	Grain yield	Haulm yield	Hundred seed weigh	Number of Pods/plant
Eberhart & Russell	1 2 3	SB16-5A SB20-2A SB19-3	SB19-3 SB16-5A SB8-1	SB20-2A SB1-1 SB4-4	SB19-3 SB4-4 SB8-1
Wricke	1 2 3	SB19-3 SB16-5A SB7-1	SB19-3 SB20-2A SB8-1	SB4-4 SB1-1 SB20-2A	SB4-4 SB19-3 SB7-1
Cultivar Superiority	1 2 3	SB4-4 SB1-1 SB19-3	SB8-1 SB1-1 SB20-2A	SB1-1 SB4-4 SB19-3	SB20-2A SB9-1 SB7-1
AMMI Stability Value (ASV)	1 2 3	SB7-1 SB9-1 SB19-3	SB8-1 SB7-1 SB9-1	SB4-4 SB1-1 SB20-2A	SB19-3 SB7-1 SB4-4
Mean yield from a combined ANOVA	1 2 3	SB4-4 SB1-1 SB19-3	SB8-1 SB20-2A SB1-1	SB1-1 SB4-4 SB19-3	SB20-2A SB9-1 SB7-1

4.7 The effect of environment on protein quantity

Table 4.16 indicates the protein content of bambara groundnut in separate trials and across localities. The average protein content for location 1 was 23% with the means ranging from 21.81 to 25.51%. SB16-5A had the highest protein value followed by SB4-4. The genotypes with the lowest protein values were SB1-1 and SB9-1. At location 2, SB4-4, SB16-5A and SB19-3 had the highest protein content of 26%, with average protein content of 24.79%. The means varied from 23 to 26%. SB1-1, SB8-1, SB9-1 and SB20-2A were genotypes with the lowest protein content. The means at location 3 ranged from 21.58 to 23.90%. The genotypes with the highest protein content across localities were SB4-4, SB16-5A with about 25% followed by SB7-1 and SB19-3 with about 24%. SB1-1 had the lowest protein content of 22%. The means ranged between 22 to 25%, with an average protein content of 23.75%. Location 2 gave the highest protein content when comparing the three localities. Overall SB16-5A and SB4-4 had the highest protein content.

The protein content was significantly affected by genotype and environment, but was not significantly affected by genotype with environment interactions. Genotype was the main source of variation with 32.48% followed by environments with 26.32% and gxe interactions with only 14.03%. The mean protein content across localities was 24%. Bradbury et al. (1985) reported that location effects affect protein content in sweet potato. His findings agree with our results. In a summary of results reported on the effects of environmental and genetic factors on various legume grains it was indicated that environmental location-year influence yield and affect protein content and quality (Anonymous, 2001).

Table 4.16 Protein content of eight bambara groundnut genotypes for three separate and combined locations.

Cultivars	Loc1	Loc2	Loc3	Combined
SB1-1	21.81	23.25	21.58	22.21
SB4-4	24.28	26.38	23.35	24.67
SB7-1	23.13	25.01	23.90	24.01
SB8-1	22.95	23.81	22.81	23.19
SB9-1	22.40	24.35	23.29	23.35
SB19-3	23.33	26.03	23.49	24.28
SB16-5A	25.51	26.05	23.16	24.90
SB20-2A	23.85	23.45	22.95	23.41
Mean	23.40	24.79	23.06	23.75
$LSD_{(0.05)}$	1.683	2.510	1.634	1.040

Table 4.17 Mean square values of eight bambara groundnut genotypes for protein content from a combined analysis of variance.

Source of Variation	Location 1	Location 2	Location 3	Combined
Genotypes	2.642	3.154	0.094	4.704**
Environments/Loc	-	-	-	13.345**
Gxe interaction	-	-	-	1.016^{ns}
C.V.	3.80	5.35	3.74	4.41

** $p \leq 0.01$

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Bambara groundnut *(Vigna subterranea)* is an indigenous leguminous crop, which plays an important role in the traditional diets of rural people in most developing countries and helps to overcome Kwashiorkor, the common protein deficiency disease in young children. The yield and protein content of crops are affected by agronomical practices and environmental conditions such as planting dates, temperature, soil type, rainfall etc., therefore these factors need to be understood in order to achieve stable and increased yield and protein content.

The overall mean grain yield of 1605 kg/ha across locations is acceptable even though it is less than the 3000 kg/ha, which Swanevelder obtained at ARC-GCI. Vaalharts locations gave the highest yield when compared to Taung and Potchefstroom because it was supplemented with irrigation; therefore to increase yields of bambara groundnut not much irrigation must be applied at the early stage to improve chances of good yields. SB4-4 was the highest yielding genotype.

Different stability parameters were used to determine stable yields, this aided in enhancing the prediction of genotype performance. Wricke's ecovalence was similar to ASV stability measures and AMMI model in selecting the most stable genotypes, where SB7-1. SB7-1 and SB19-3 were ranked first and third by ASV and third and first respectively by Wricke's ecovalence value. AMMI analysis gave the best performance as a stability analysis tool. Multilocational trials help to estimate yields accurately and understand interactions of genotype with environments, but it does not include the interaction of genotype with year effect and does not really give the stability of yield. Therefore it is recommended that the trials be repeated over consecutive seasons to determine if the rankings of genotypes will be stable across locations and years. It will then be easier to select stable genotypes that can be used for breeding purposes.

Yield was closely related to seed size. Large seed sizes resulted in higher yields. For breeding purposes, genotypes with large seeds and stable yields should be selected and used for hybridizations to develop high yielding and stable cultivars that will be acceptable to farmers. In terms of breeding, genotypes recommended for crossing blocks would be SB7-1, SB19-3, SB4-4 and SB1-1. Cultivars, which should not be used as crossing parents, are SB20-2A, SB8-1, SB16-5A and SB9-1 because of their low yield and instability.

In terms of production Vaalharts will be best suited for planting bambara groundnut when supplementing the trials with irrigation. Taung1 and Potchefstroom 1 were the best environments for cultivation of bambara groundnut under dry land conditions. The best cultivars for production are SB4-4 and SB1-1.

Planting date did not have any significant influence on the grain yield of eight bambara groundnut genotypes. The protein content of 25% obtained in this study compares well with that of similar grain legumes such as cowpea and chickpea; therefore it can be used in place of these legumes to supplement cereals dishes. Locality 2 gave the highest protein content when compared to other localities.

CHAPTER 6

SUMMARY

Key terms: Bambara groundnut; *Vigna subterranea*; genotype; localities; genotype x environment interaction; correlation matrix; planting date x genotype interactions; protein content/quantity; yield stability; yield components;

- This study was undertaken to evaluate genotype x environment interaction (gxe) and yield stability of eight bambara groundnut genotypes in three locations at two planting dates; to compare the stability parameters used in determining stable yields, to correlate yield and related characters of the crop, to determine the effect of planting date on yield and yield components; and to assess the effect of location and genotype on protein content.

- Field trials were planted with two different planting dates in three localities. A randomized complete block design with three replications was used. Data collected was days to 50% flower, number of pods per plant, grain yield, haulm yield, 100 seed weight, and maturity days.

- Data was subjected to simple ANOVA's for all measured characteristics. Significant differences were found for most of these characteristics. Combined analyses of variance were computed across locations to determine the performance of yield and related characteristic. Significant differences were found for genotype, environment and Gxe interactions. The best genotype was SB4-4 across locations.

- Four stability parameters namely Eberhart and Russell regression model, Lin and Binns' Cultivar Superiority Measure (P*i*), Wricke ecovalence (W*i*) and Additive Main Effects and Multiplicative Interaction (AMMI) were performed to determine yield stability. SB16-5A was regarded the most

stable by Eberhart and Russell, SB19-3 by Wricke ecovalence, SB7-1 by ASV and SB4-4 by cultivar superiority and yield rankings The results showed that SB19-3 was the third most stable genotype according to Eberhart and Russell and Lin and Binns yield ranking; and the first and second most stable genotypes by the Wricke and AMMI model. Therefore SB19-3 proved to be the most stable genotype. ASV and Wricke ecovalence value ranked SB4-4 and SB1-1 to be the first and second most stable genotypes for 100 seed weight, while ranking SB19-3 first and second respectively for number of pods per plant. The AMMI model summarizes patterns and relationship between gxe interactions and helps to obtain a good yield estimates. The results for stability of yields are not conclusive since the data is for one season, therefore the trials must be repeated to validate the results.

- Correlation analyses were first computed for separate trials and then for combined trials across locations. Hundred seed weight, haulm yield, number of pods per plant and root weight were positively correlated with grain yield with haulm yield and 100 seed weight having strong positive correlations to grain yield. Planting date did not significantly affect yield and protein content was also not significantly affected by gxe interactions.

OPSOMMING

Sleutel terme: Bambara grondboon; *Vigna subterranea*; genotipe; lokaliteite; genotipe x omgewinginteraksie; korrelasie matriks; plantdatum x genotipe interaksies; proteïeninhoud/kwantiteit, opbrengs stabiliteit; opbrengskomponente

- Hierdie studie is onderneem om genotipe x omgewingsinteraksie (gxe) en opbrengs stabiliteit te evalueer van agt bambara grondboon genotipes in drie lokaliteite met twee plantdatums; om stabiliteitsparameters te gebruik om stabiele opbrengste te bepaal; om korrelasies tussen opbrengs en opbrengskomponente te ondersoek; om die effek van plantdatum op opbrengs en opbrengskomponente te bepaal, en om vas te stel hoe die proteïeninhoud deur omgewing beïnvloed word.

- Veldproewe is by twee plantdatums geplant by drie lokaliteite. ‘n Gerandomiseerde blokontwerp is gebruik met drie herhalings. Data is ingesamel vir dae tot 50% blom, aantal peule per plant, opbrengs, 100 saadmassa en dae tot volwassenheid.

- Data is onderwerp aan eenvoudige ANOVA’s vir alle gemeette eienskappe. Betekenisvolle verskille is vir meeste eienskappe gevind. Gekombineerde variansie analise oor alle lokaliteit is gedoen vir alle eienskappe. Betekenisvolle verskille is gevind vir genotipe, omgewing en die interaksie tussen die twee. Die beste genotipe was SB4-4 oor die lokaliteite.

- Vier stabiliteits parameters naamlik die Eberhart and Russell regressie model, Lin en Binns se cultivar superioriteits meting (P*i*), Wricke se ekovalensie (W*i*) en die Additiewe Hoof Effekte en Veelvoudige Interaksie (AMMI) is gedoen om opbrengs stabiliteit te bepaal. SB16-5A was die mees stabiel volgens Eberhart en Russell, SB19-3 volgens Wricke se

ekovalensie, SB7-1 deur die ASV en SB4-4 deur cultivar superioriteit en opbrengs rangorde. Die resultate het getoon dat SB19-3 die derde mees stabiele genotipe is volgens Eberhart en Russell en Lin en Binns se opbrengs rangordes; en eerste en tweede mees stabiel deur Wricke en die AMMI model. Daarom was SB19-3 die mees stabiele genotipe. ASV en Wricke se ekovalensie het SB4-4 en SB1-1 as die eerste en tweede mees stabiele genoptipes uitgewys vir 100 saadmassa, terwyl SB19-3 eerste en tweede was vir aantal peule per plant. Die AMMI model som die patrone en verwantskappe op vir gxe interaksies en help om goeie opbrengs voorpellings te maak. Die resultate vir die opbrengs stabiliteit is nie finaal nie, en meer as een seisoen se data sal ingesluit moet word om werklik sinvolle afleidings te maak.

- Korrelasies is eers bepaal vir afsonderlike lokaliteite, en daarna vir gekombineerde data oor lokaliteite. Honderdsaadmassa, biomassa, aantal peule per plant en wortelmassa was positief gekorreleer met opbrengs. Biomassa en 100 saadmassa het sterk positiewe korrelasie gehad met opbrengs. Plantdatum het geen betekenisvolle effek gehad op opbrengs nie. Proteïeninhoud is ook nie betekenisvole deur gxe interaksies beïnvloed nie.

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