Genetic Analysis of Agronomic and Quality Traits in Popcorn Hybrids

By

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A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science in Plant Breeding

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Republic of South Africa

February 2012

GENERAL ABSTRACT

Popcorn is increasingly becoming popular as a snack and is consumed widely all over the world. It is a high value crop, with possible multiplier effects like income generation for the under-resourced communities in the second economy. Despite its popularity, developing countries are battling to meet the demand and rely on importing popcorn grain due to challenges which include poor agronomic traits and slow breeding progress. Most of the imported varieties are not adapted to stress-prone local environments, which are prevalent in tropical sub-Saharan Africa.

The objective of the study was to evaluate newly developed hybrids and inbred lines for agronomic and popping quality traits with the possibility for commercialization in future. The study aimed at determining variability for popping ability in inbred lines and hybrids, grain yield and its secondary traits, the nature of gene action, relationships among agronomic and popping quality traits, effect of genotype x environment interaction on agronomic traits and popping method x genotype interaction effects.

To determine popping ability, 128 inbred lines were evaluated at the University of KwaZulu-Natal, South Africa, in June 2011 using two popping methods, the microwave method and the hot-air method. The popping quality attributes measured were flake volume, popping fold, number of unpopped kernels, kernel size and quality score. Variability among inbred lines was significant ($P<0.05$) for all traits. Flake volume ranged from 63 cm^3 to 850 cm^3, popping fold ranged from 2.5 to 34 times the original volume. Kernel size had a significant positive correlation ($r= 0.49$) with the number of unpopped kernels. There was a significant strong and negative correlation between flake volume and the number of unpopped kernels ($r= -0.62$), indicating that either of the two traits would be effective for measuring popping ability.

Experimental hybrids were then developed from 87 out of the possible 128 inbred lines. Only the inbred lines with sufficient seed were crossed to develop hybrids. Random crosses were generated at Makhathini Research Station during the winter season of 2011. Crosses were made at random among parents that managed to synchronize their flowering dates, resulting in 119 hybrids with sufficient seed for planting in trials.

To determine agronomic superiority, the 119 experimental hybrids and the standard check P618 were evaluated at the Cedara Research Station and Ukulinga Research Farm in the Midlands of KwaZulu-Natal during the summer of 2011/2012. The experiments were laid out as 10 x 12 alpha lattice design, with two replications at each site. Standard cultural practices for maize were followed. The data were subjected to analysis of variance and line x tester analysis in Genstat and SAS statistical programmes. Results indicated that hybrids were significantly different for all agronomic traits. Means for grain yield ranged from 1.0 t/ha to 5.2 t/ ha. General combining ability effects were significant for all agronomic traits, suggesting that additive gene effects were governing these traits. Specific combining ability effects were significant for ear length, number of ears per plant and yield indicating, that non-additive gene effects were influential for these traits. Generally, agronomic traits were highly heritable. Grain yield showed significant and positive correlation with ear length, plant height, ear position, shelling percentage and number of ears per plant, indicating that these were the major yield-determining secondary traits which should be enhanced in popcorn. Although site main effects were highly significant for secondary traits, the hybrid x site interaction was not significant. The results therefore indicate that the hybrids were ranked similarly at both sites.

The 119 experimental hybrids and the standard check P618 were evaluated for popping quality, using the microwave and the hot-air popping method. There was a significant variability observed among hybrids for popping quality traits. Flake volume across sites and across popping methods ranged from 734 cm^3 to 1288 cm^3. Popping fold ranged from 14.69 to 25.75 times the original volume. Additive gene action was more prominent than non-additive action for all popping quality traits. The SCA effects were significant for flake volume, popping fold and number of kernels per 10 g. All popping quality traits had high heritability, indicating that selection would be effective to improve popping. Flake volume was negatively correlated to quality score, indicating that popping expansion is reflected on the quality score and a significant negative correlation between flake volume and number of unpopped kernels. There was significant and strong positive correlation between kernel size and number of unpopped kernels. Hybrid x site interaction was only significant for quality score and kernel size. Hybrid x method interaction was not significant, indicating that popping ability was not dependent on the method.

Inbred lines showed significant variation for popping quality and therefore have utility for hybrid development. Significant genotypic variation was also observed among hybrids for agronomic and popping quality traits. Additive gene action was predominantly responsible for both agronomic and popping quality traits. Both agronomic and popping quality traits were highly heritable and positive relationships were identified among traits. Overall, the study indicates opportunities for further breeding progress through selection.

DECLARATION

I, Collinet Phumelele Jele, declare that:

1. The research reported in this dissertation is my original research, except where indicated otherwise.

2. This dissertation has not been submitted for any degree or examination to any other university.

3. The dissertation does not contain graphics, text or tables that have been copied and pasted from the internet, unless specifically acknowledged and referenced.

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Signed

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Collinet Phumelele Jele

As the candidate’s supervisors, we agree to the submission of this dissertation:

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(Co-Supervisor)

ACKNOWLEDGEMENTS

I would like to extend gratitude to the National Research Foundation, for providing the study grant to make the study possible.

I am forever grateful to my supervisors, Professor John Derera and Dr Muthulisi Siwela, for the unwavering support, guidance and inspiration they gave me. Their continued dedication and constructive criticism have given me the courage to get this far. Thank you for believing in me and encouraging me to persevere through and through.

I would like to thank the Department of Agriculture and Environmental Affairs in KwaZulu-Natal for providing the bursary towards tuition and other invaluable support in ensuring the success of the project. I would like to thank, in particular, Mr. Z.S. Khoza and Mr. Z. Dlamini for their continuous support and encouragement.

A special thanks to Miss Fikile Qwabe, who was the pillar of my strength, always there for me in trying times. May God grant you the blessings you deserve.

I am grateful to the dedicated research team from the University of KwaZulu-Natal, for being thorough and always dedicated while managing the trials.

DEDICATION

This dissertation is dedicated to my father, Bhekinkosi, my mother, Thengaphi, Themba Masikane and my sons, Luthando Ndabezinhle and Nkosivumile, Awande.

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Popcorn (*Zea mays* L. *everta*) is a special type of flint maize that has the ability to pop when kernels are subjected to high temperatures and produces flakes which are widely used as a snack. It has been reported that popcorn is an old crop which already existed long before the USA was discovered in 1492. The USA is the world leader in the production and consumption of popcorn, where annual consumption is estimated at 4.5 billion tons (Sweley *et al.*, 2011). Popcorn is popular and is consumed by people of all ages throughout the world (Park and Maga, 2001; Karababa, 2006; Ertas *et al.*, 2009). Popcorn is consumed in movie theatres, sports venues and in homes across the globe. Nutritionally, popcorn is classified as a healthy whole-grain snack, because it is high in fibre, to provide the body with roughage and carbohydrates and is recommended for being low in sodium, fat and calories (Kulp and Ponte Jr., 2000). Popcorn is recognized as a high value crop (Santacruz-Varela *et al.*, 2004; Babu *et al.*, 2006). In Brazil, the price of popcorn grain is reported to be three times that of dent maize (Moterle *et al.*, 2012). In 2004, the USA generated a turnover of 1.5 billion dollars from popcorn sales and this figure has increased steadily over the years (Sweley *et al.*, 2011). Developing countries such as India, Brazil and Turkey are gradually increasing popcorn production due to the economic value of the crop (Vieira *et al.*, 2009; Vijayabharathi *et al.*, 2009b; Oz and Kapar, 2011). In Africa, the economic importance of the crop has also been recognized (Iken and Amusa, 2010).

1.2 Quality and agronomic aspects of popcorn

Popcorn kernels are characterized by large amounts of hard endosperm, as opposed to soft endosperm, and a very thick pericarp (Ziegler, 2001). Both parts are crucial in the popping mechanism (Hoseney *et al.*, 1983). The pericarp of dent maize is porous and the endosperm is mostly soft, and these traits are not conducive to popping. The popcorn kernel consists of the thickest pericarp of all maize types. Some varieties of flint maize have the ability to pop and produce flakes, but none of them exhibit popping volumes comparable to those of popcorn (Ziegler, 2001; Babu *et al.*, 2006). Popping volume or popping expansion is the most important quality trait in popcorn and is defined as the ratio of flake volume to the original weight of unpopped kernels. The traits associated with expansion volume are the number of unpopped kernels and grain moisture content at the time of popping (Singh and

Singh, 1999; Soylu and Tekkanat, 2007). Good quality popcorn needs to have good kernel colour, must be free from hulls, have a good flavour, tenderness and good popping expansion. There are three popular methods of popping, hot oil popping, hot air popping and microwave popping. Popping ability therefore sometimes depends on the method used for popping, which leads to complications of genotype by method interaction effects.

In addition to popping ability, yield is very important to justify value for cultivation and use of popcorn. Yield and its secondary traits need to be improved simultaneously with popping ability to be useful in breeding programmes. In popcorn, yield has been found to be negatively associated with popping ability, hence the slow breeding progress in popcorn compared to dent maize (Ziegler, 2001). In addition, Africa is mostly characterized by stress-prone environments like widespread drought and disease incidence. Introgression of disease resistance therefore needs to form an integral part of popcorn breeding programmes in the continent.

1.3 Constraints in popcorn production

Progress in popcorn breeding has been slow in developing countries, due to challenges of inferior germplasm and poor agronomic traits of popcorn varieties. Countries such as South Africa depend on imported seed for popcorn production. These imported varieties are not adapted to local conditions and this has led to widespread crop failures, partly due to susceptibility to diseases like northern corn leaf blight (NCLB), which can lead to yield losses of 30-68% (Freymark *et al.*, 1993). In South Africa, breeding efforts targeted at popcorn were last reported in 1954 (Josephson *et al.*, 1954). The challenges associated with popcorn are a major limiting factor to its production in Africa and this calls for more relevant breeding programmes aimed at broadening the genetic base and developing suitable locally adapted varieties.

1.4 Specific objectives

The specific objectives of this study were:

a) To evaluate inbred lines for popping ability
b) To evaluate hybrids for agronomic traits such as grain yield and secondary traits
c) To determine gene action for popping and agronomic traits
d) To evaluate hybrids for popping ability
e) To investigate relationships between traits in hybrids.

1.5 Hypotheses tested

The research project tested the following hypotheses:

a) Economically important traits in popcorn are influenced by additive gene action
b) There are significant positive relationships between traits that can be exploited in breeding popcorn hybrids.
c) There are significant differences between inbred lines for popping
d) There are significant differences among hybrids for popping and yield.

1.6 Dissertation outline

The dissertation is outlined in chapters as follows:

1. Introduction to dissertation
2. Literature study
3. Assessment of inbred lines for popping ability
4. Assessment of agronomic traits in popcorn hybrids
5. Assessment of popping ability in popcorn hybrids
6. General discussion, conclusion and recommendations
   Appendices

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LITERATURE STUDY

2.1 Introduction

This chapter includes a review of the global importance of popcorn, its nutritional value and its utilization. The agronomic aspects and production challenges are reviewed, together with kernel morphology, quality aspects and the popping mechanism. Breeding aspects, which include combining ability, breeding methods, gene action and relationships among agronomic and quality traits, are also discussed. Due to the limited literature on popcorn breeding, the breeding methods applicable to popcorn and maize in general have been discussed.

2.2 History and origin of popcorn

It is reported in the literature that popcorn existed long before America was discovered by Christopher Columbus in 1492. By then, more than 700 popcorn types were being cultivated in Europe. Popcorn is thought to have originated from South and Central America. During the Great Depression, which occurred between the late 1920s and early 1940s, popcorn was very cheap, costing around 10 American cents per bag. It was during this time that it became popular. While other businesses failed, the popcorn business thrived and became an important source of income to struggling farmers. When sugar rations for making candy were diminished during World War II, circumstances pushed popcorn consumption up three-fold. Popcorn was further made popular by the invention of the electric popping machine in 1925 and that of the micro-wave oven in 1945 by Percy Spencer (The Popcorn Board, 2010).

Before 1900, popcorn was grown as a garden crop. Popcorn was recognized as a legitimate cash crop around 1890. It was commercialized around 1912, when it was produced on about 8000 hectares of land in the USA. The area under production increased to around 80 000 hectares per annum between 1977 and 1981 (Ziegler *et al.*, 1984). Annual production currently stands at about 295 000 tons. The first commercial production data on yields, gross margins and product price became available between 1925 and 1941, coming mostly from the state of Iowa in the USA (Ziegler, 2001).

2.3 Global importance of popcorn

Popcorn (*Zea mays* L. *everta*) is widely consumed all over the world (Park *et al.*, 2000; Karababa, 2006; Ertas *et al.*, 2009). Unlike dent maize, which is milled for human food products and animal feed, it is utilized primarily as a snack (Johnson, 2000). Popcorn is a special type of flint maize with the ability to pop into flakes which are sought after as a whole-grain snack. Popcorn has long been recognized as a crop of economic importance and high value (Santacruz-Varela *et al.*, 2004; Babu *et al.*, 2006). In Brazil, the price of popcorn is reported to be three times that of dent maize (Moterle *et al.*, 2012). The price of popcorn grain in South Africa is more than three times that of dent maize (personal observation). In October 2012, the average retail price of popcorn grain was R12 000 per ton, compared to R2200 per ton for dent maize (South African Grain Information Service, 2012). The relatively high prices of popcorn may be attributed to the fact that there are no locally adapted varieties of popcorn with desirable traits that can be produced locally, despite the growing consumption of popcorn in South Africa, especially in cinemas across the country. Popcorn is consumed mostly in cinemas throughout the world, including South Africa. Home consumption of popcorn is also very popular after microwave ovens became commercially available in the 1980s. Hot-air popping machines are available in the market to make home popping convenient. Popcorn flakes are either for fresh popping or for the confection industry.

The United States is the world leader in the production and consumption of popcorn. The consumption of popcorn in the USA is estimated at 4.5 billion tons of grain, which works out to 1.36 kilograms of popped corn per person per annum (Sweley *et al.*, 2011). Americans consume 16 billion litres of popcorn flakes per year, with 70% consumed in homes and 30% in movie theatres. Popcorn is also consumed in large quantities in stadiums during sporting events and schools (Ziegler, 2001). Popcorn produced in the USA is exported to 90 countries, including South Africa. Among the developing countries, Mexico, Brazil and Argentina are becoming important players in popcorn production. By 2004, 75% of popcorn consumed in Brazil was imported from the USA (Daros *et al.*, 2004). In the same year, the USA generated a turnover of 1.5 billion dollars from popcorn sales. Due to limited popcorn breeding programmes, Turkey was importing popcorn in 2005 (Sakın *et al.*, 2005). Turkey still imports popcorn for consumption due to shortage and high demand (Oz and Kapar, 2011). In India, popcorn is produced on a small scale. Like other developing countries, India faces the limitation of low quality due to slow progress in developing adapted varieties. The popping ability of Indian popcorn varieties is reported to be half of American hybrids, due to lack of adaptability (Vijayabharathi *et al.*, 2009b).

2.4 Popcorn production in Africa

According to the literature, there is no indication that popcorn is produced locally. There is a general lack of information on the breeding, production and marketing of popcorn in South Africa. Grain South Africa, the custodian of information in grain production and marketing, has no information recorded on popcorn. Most popcorn consumed in South Africa is imported from developed countries. Despite the fact that popcorn is gaining popularity in Africa, like the rest of the world, the continent is lagging behind in developing suitable varieties required to produce popcorn on a commercial scale. There are reports that popcorn consumption is gaining popularity in Nigeria (Agele *et al.*, 2008; Iken and Amusa, 2010). Information on production and consumption trends is not well documented in the literature. This seems to be due to lack of focus on popcorn production and breeding programmes in Africa. As indicated earlier, popcorn is a high value crop, with possible multiplier effects for both commercial and small-holder farmers. Africa as a continent needs to pay more attention to devising relevant popcorn breeding programmes, as well as monitoring production and marketing information, to be able to benefit from vast economic opportunities presented by commercial popcorn production.

2.5 Morphology of a popcorn plant

The morphology of the popcorn plant is in many ways very similar to a normal maize plant. The plant has conspicuous nodes and internodes on the stem. Leaves grow on opposite sides of the stem, with one leaf growing per node. The plant is monoecious since the male and female inflorescences grow separately on one plant. Popcorn, like normal maize, is cross-pollinated, which leads to naturally heterogeneous populations. This has implications in the breeding methods than can be applied successfully in popcorn improving programmes. The popcorn plant is known for being shorter, in most cases, and weaker than that of dent maize, especially inbred lines and open-pollinated varieties. Reports indicate that some popcorn hybrids in tropical environments can be as tall as, or taller, than those of dent maize hybrids (Ziegler, 2001). This is due to heterosis associated with hybrids.

The popcorn plant consists of adventitious and prop roots, stalk, leaves, nodes, tassel, ear and husk. Adventitious roots are located below the ground and serve to anchor the plant as well as absorb water and nutrients. Prop roots are located above the ground and give extra support to the plant. The root system of popcorn is less extensive than that of normal maize. Popcorn is thus adversely affected by poorly drained soils (Ziegler *et al*, 1984).The stalk is the main stem which supports the plant. The stalks are thin and weak, which makes popcorn susceptible to lodging (Mani and Dadari, 2003; Babu *et al.*, 2006; Li *et al.*, 2008; Trindade *et al.*, 2010). Popcorn leaves, like those of dent maize, grow out from the nodes. The nodes separate the stem into sections. The nodes serve to strengthen the plant and prevent breaking. The leaves are parallel-veined like those of dent maize, but narrower and more upright orientated.

Growth stages of a popcorn plant are separated into seedling growth, vegetative growth, flowering and fertilization and lastly, grain filling and maturity. The tassel is the male flower and is located on top of the plant. The popcorn tassel is more pronounced than that of maize and tends to have a drooping appearance. The popcorn tassel produces more pollen than dent maize due its large size (Ziegler, 2001). Anthesis (production of pollen) is the critical stage to monitor as it may lead to failure of pollination in a breeding programme. Male flowers mature before the female flowers. The period between silking and anthesis is called the anthesis-silking interval. Under favourable conditions, silks appear 1 to 3 days after anthesis, which is the ideal synchronisation of pollen and silk, leading to effective pollination. Fertilization occurs within 12-28 hours of pollination. The ear shoots are shorter than those of maize. Top ear placement tends to be higher, which adds to complications due to lodging. High ear placement is not desirable, as it makes harvesting difficult. Yields are lower, usually half that of maize hybrids (Ziegler *et al.*, 1984). Popcorn seed tends to germinate more slowly than maize. Prolificacy is very common in popcorn.

2.6 Kernel morphology of popcorn and other specialty maize types

Popcorn kernels are unique in many ways and are the main factor which distinguishes it from other types of maize. Popcorn can be viewed as small-kernelled, flint-type corn (Dickerson, 2003). Based on kernel morphology, texture, usage, functionality and other characteristics, maize can be classified into specialty types, which include waxy maize, high protein maize, high oil maize, flour maize, sweet-corn and popcorn (Johnson, 2000). Kernels of flint maize are hard and contain mostly hard endosperm. They have a glassy appearance. They are smooth and rounded and are associated with high popping ability (Song *et al.*, 1991). The popcorn kernel consists of the pericarp, endosperm and the embryo or germ. The endosperm forms the major part of the kernel (Johnson, 2000). Popcorn is unique from dent maize in that consists almost entirely of hard or corneous endosperm. The corneous endosperm is made of compact starch granules, with no air spaces, and has a glassy appearance (Broccoli and Burak, 2004). The morphology and endosperm types of the different maize types are shown in Figure 2.1.

Kernels of dent maize on the other hand are characterized by the presence of a small proportion of corneous or hard endosperm at the side and back of the kernel (Johnson, 2000). The kernel inner core consists of soft floury endosperm, which extends to the crown of the endosperm. Kernels of dent maize are not adapted for popping due to large amounts of soft endosperm. The popcorn kernel is almost half the size of dent maize (Ziegler, 2001).

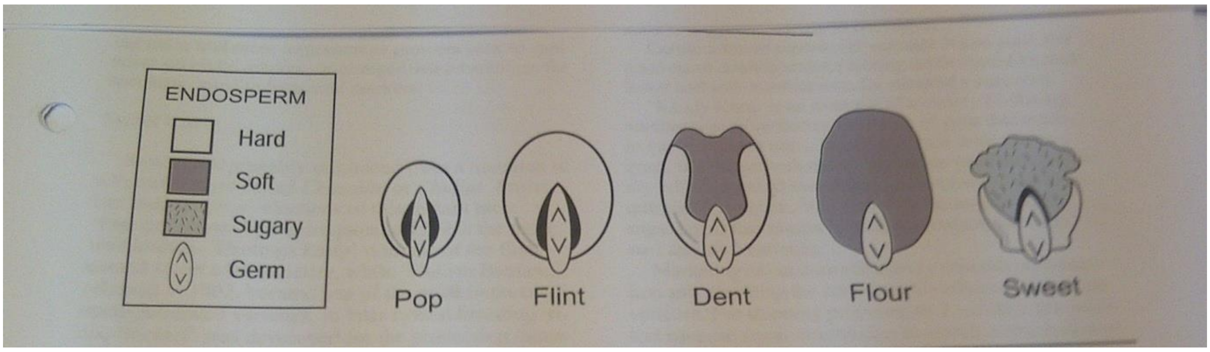

Figure 2. 1: Kernel morphology and endosperm type for different maize groups.

(Dickerson, 2003)

The second unique feature of the popcorn kernel is that it has a very hard outer covering called the pericarp, which is capable of exploding when subjected to high temperatures (Babu *et al.*, 2006; Karababa, 2006). The popcorn kernel consists of the thickest pericarp of all maize types (Ziegler, 2001). It is, however, reported that some popcorn varieties, especially Argentine semi-primitive popcorn has thin pericarps, usually associated with low popping volumes. The thick pericarp has been reported to have the greatest effect on popping expansion both in the conventional and microwave method of popping (Hoseney *et al.*, 1983). A damaged pericarp can lead to low popping expansion (Singh *et al.*, 1997). In terms of functionality, popcorn is distinct from other types of maize because of its ability to explode (pop) when exposed to heat. The popcorn kernel explodes and turns inside out at temperatures between 170^{o}C and 180^{0}C. It has been reported that popping occurs at a temperature of 243^{0}C, using a Metric Weight Volume Tester (Song *et al.*, 1991). Previous reports indicate that popcorn pops at temperatures ranging between 180^{0}C and 190^{0}C (Byrd and Perona, 2005). Another view indicates that popping was achieved at a temperature of 177^{0}C. Very little popping can be achieved below this temperature (Hoseney *et al.*, 1983).

Popcorn kernels occur in various colours, from red, black, brown, orange, yellow and white. Orange and yellow kernels are the ones that are used commercially (Ziegler, 2001). Popcorn kernels can be distinguished into two types, the rice type and the pearl type. Varieties with white kernels are usually associated with the rice type kernel, while pearl types are commercially associated with yellow kernelled popcorns (Ziegler, 2001; Karababa, 2006). The pearl-type kernels are the most common, commercially, and they have smooth, pearl-like crowns. Rice types are long and pointed at the end.

Size of popcorn kernels is divided into small, medium and large, as shown in Table 2.1. Kernel size is determined by counting the number of kernels per 10 grams of grain.

Table 2. 1: Classification of popcorn kernels by size

No of kernels per 10g	Size classification
52-67	Large
68-75	Medium
76-105	Small

(After Ziegler *et al.*, 1984)

Medium-sized kernels are appealing to both home consumers and processors. Small kernels are preferred by home consumers because they tend to produce small, but tender flakes, with few hulls. Vendors prefer large flakes for good eye appeal. They are also tougher, so that they do not break easily.

The popcorn kernel has a tough, impermeable outer hull, which is necessary for a kernel to pop. There is, therefore, no completely hull-less popcorn varieties. The so-called hull-less varieties are selected to have smaller kernels, so that a resulting flake after popping has a less pronounced hull. Some hybrids have been selected for a quality trait called hull dispersion, whereby the hull disperses to smaller units after popping (Ziegler, 2001). A conspicuous hull is not desirable in popcorn because it gets stuck between the consumer’s teeth and causes irritation.

2.7 Nutritional composition of popcorn

As stated earlier, popcorn contains several nutrients, mainly carbohydrates, fat, protein, minerals and vitamins. The nutritional composition of popcorn is shown in Table 2.2.

Popcorn is a whole-grain snack which is considered by the 2005 Dietary Guidelines for Americans as the nutritionally valuable all-round snack food. Whole-grain snacks are associated with improved weight management towards reduction of chronic diseases like diabetes and coronary heart disease (Grandjean *et al.*, 2008). It provides protein, roughage, iron, calcium, energy, fibre, vitamin A and a variety of B vitamins. The fibre contained in popcorn is well balanced into soluble and non-soluble fibre and is well suited to protect beneficial bacteria in the gut. It is classified as a healthy whole-grain snack because it is high in fibre to provide the body with roughage. It is high in complex carbohydrates and low in sodium, fat and calories (Kulp and Ponte, 2000). Popcorn has been recommended by the National Cancer Association, American Dental Association and American Dietetic Association as a sensible snack that can fit a good meal plan (Grandjean *et al.*, 2008).

Popcorn is sold as flakes after popping. It is sold either plain or with flavours added. It is sold as freshly popped corn or popcorn confections. Recently, due to the popularity of microwave popping, bags of unpopped kernels are available on the market. Flavours are usually included in the bag. Popcorn flavour is commonly improved by adding salt and butter (Carter *et al.*, 1989). The number of calories increases with the addition of butter or oil. Yellow or orange popcorn and other yellow or orange maize varieties may contain nutritionally significant amounts of vitamin A. The vitamin A in the yellow or orange popcorn is in the form of provitamin A carotenoids. Provitamin A carotenoids are precursors of vitamin A and they include beta-carotene, alpha-carotene and beta-cryptoxanthin. Other non-provitamin A carotenoids, lutein and xeaxanthin, have been found to co-exist with the provitamin A carotenoids (Menkir *et al.*, 2008).

Table 2. 2: Nutritional composition of popcorn

Nutrient	**Content (g/100g)**
Starch	62.3
Protein	11.9
Fat	5.3
Total minerals (ash)	1.9
Fibre	9.3
Niacin	0.2 - 0.6 mg/cup*
Iron	0.4 - mg/ cup*
Calcium	2 mg/ cup*

(after Johnson, 2000) * (IASRI, 2009)

The nutritional composition of popcorn may vary with varieties, the environment and the manner in which it is prepared. However this has not been reported in the literature. The nutrients reported in Nigerian popcorn hybrids include 64% carbohydrate, 8.7% protein and 8.8% fat (Ademiluyi and Oduola, 2011). Microwave popping and hot air popping are therefore the preferred methods for the health conscious, since they provide an option of popping without fat.

2.8 Popcorn quality

In popcorn, popping ability is a critical quality trait, in addition to good agronomic traits (Sakın *et al.*, 2005). The popped volume is of great importance to the consumer (Hoseney *et al.*, 1983; Song *et al.*, 1991; Shimoni *et al.*, 2002). Studies indicate that consumers prefer popcorn that is tender, fluffy and with a high expansion volume (Allred-Coyle *et al.*, 2000). Quality in popcorn is measured firstly by expansion volume, which is affected by other quality factors. This is a ratio of flake volume to the original weight of unpopped kernels. This trait distinguishes popcorn from other forms of maize. The expansion volume or popping volume is affected by the percentage or number of unpopped kernels (Singh and Singh, 1999; Soylu and Tekkanat, 2007), kernel size (Song *et al.*, 1991) and grain moisture content at the time of popping. Popping quality parameters of importance for determining quality are expansion volume, popping fold, flake size and number of unpopped kernels. Popping fold is a parameter that measures how much the kernel expands after popping. Commercial buyers buy kernels by weight and sell by volume of popped corn. Some varieties of flint maize have the ability to pop and produce flakes, but none of them inhibit popping volumes of popcorn (Ziegler, 2001; Babu *et al.*, 2006). Most commercial popcorn varieties expand 30-40 times their volume (Dickerson, 2003). Different popping methods affect expansion volume and flake size.

Moisture content of kernels at the time of popping plays a major role in determining popping quality (Metzger *et al.*, 1989; Shimoni *et al.*, 2002; Gökmen, 2004; Ertas *et al.*, 2009). To achieve optimum popping, the moisture content should be between 13 and 14.5% (Ziegler, 2001). Previous studies achieved the highest popping expansion volume at a moisture content of 14% (Gökmen, 2004; Oz and Kapar, 2011). To achieve the desired moisture content, popcorn kernels are conditioned by slow drying from the moisture content of 16-18% at harvest. It was reported that a 1% deviation from optimum moisture content could reduce the popping volume as much as 2% (Song *et al.*, 1991). Moisture content of popcorn at harvest should be 18-20% on the ear and 16-18% for shelled popcorn grain (Agele *et al.*, 2008).

Flake size is another important quality factor, because large flakes are associated with tenderness. Flakes occur as either mushroom or butterfly shape. Mushroom-shaped flakes are round, with very few wings. Most hybrids produce a combination of mushroom and butterfly flakes. The mushroom shape is preferred by the confectioners because it is less susceptible to breakage. The butterfly-shaped flakes are irregular. Butterfly-shaped flakes are inclined to be tender and are preferred by movie theatres, to be sold on the premises. They are also susceptible to breakage and cannot withstand extended handling. The change from butterfly to mushroom shape can be achieved successfully through plant breeding (Ziegler, 2001).

Popcorn quality depends on a number of factors. It needs to have a good kernel colour, be free from hulls, have good flavour, be tender and exhibit good popping expansion. Consumers look for bright coloured kernels when purchasing from retailers. Tenderness in popcorn flakes has been associated with high popping expansion (Pipolo *et al.*, 2003). Popping expansion can in turn be affected by a number of factors. Large flakes have been associated with tender flakes. Genotype and kernel size have a direct effect on popping volume (Oz and Kapar, 2011). Gökmen (2004) suggested that large kernels produced large flakes and the smallest percentage of unpopped kernels.

Both the endosperm and the pericarp play a role in the popping mechanism of popcorn. There are three popular methods of popping, hot oil popping using the pot on the stove, or hot oil popping using machines, hot air popping using machines and microwave popping. Popping method has been reported to have an effect on expansion volumes. Microwave popping has been reported to give small popping volumes and a high percentage of unpopped kernels (Gökmen, 2004). It has been reported that large kernels give high expansion volumes when using the microwave method and medium-sized kernels give high expansion volumes in the oil popping method (Karababa, 2006). The general recommendations for popping times in the microwave at full power are shown in Table 2.3.

Table 2. 3: Recommended microwave wattage (power) and time

Wattage (W)	Popping time (min)
1000	1.5 - 2
700	2.45 - 3.3
650	3 - 4
500	4.3 - 6

(after IASRI, 2009)

2.9 Challenges in popcorn production

Popcorn production lags behind that of dent maize, despite the increasing consumption levels and high economic value of popcorn, due to numerous challenges. For example, in Brazil, the economic value of popcorn is three times that of normal maize. The main cause for the discrepancy in production is the slow progress in breeding superior popcorn lines. In Brazil, popcorn breeding dates back to 1932, but reports indicate that the breeding efforts stopped around 1941, when the first national Brazilian cultivar was released, and only resumed in 1988. By the end of the 2006/2007 season, only 7 out of 278 maize cultivars in Brazil were popcorn (Rangel *et al.*, 2008).

Popcorn germplasm performs worse than dent maize (Sanches *et al.*, 2011). There is a small number of popcorn lines selected to maximize popping expansion and quality. Popcorn is not only limited in germplasm quantity, but also inferior to dent maize in yield and other agronomic traits (Babu *et al.*, 2006). Yield of popcorn hybrids is reported to be two thirds that of dent maize hybrids. Yield is highly affected by genotype (Sakın *et al.*, 2005; Vijayabharathi *et al.*, 2009b).

Other poor agronomic traits of popcorn include weak and thin stems, which promote susceptibility to root and stem lodging. Poor standing ability has a negative effect, since it prevents crop maturity. Maximum popping ability can be attained only if the crop reaches full maturity. Standing ability is an important trait in popcorn, as popcorn needs to remain on a cob much longer than normal maize to reach full maturity. Popcorn is harvested at a moisture content of between 16 and 18%. The popcorn plant must remain standing even after the stem has begun to deteriorate (Ziegler, 2003). Popcorns tend to have high ear placement, which has a negative impact on standing ability (Ziegler, 2001). Popcorn is also more susceptible to diseases and pests than normal maize. Leaf diseases cause great losses, especially in the early growth stages of the crop (Amusa *et al.*, 2005). Northern Corn Leaf Blight (NCLB) is a disease of maize which is caused by the fungus *Exserohirum turcicum*. It can cause major crop losses, especially in humid areas. Yield losses can be up to 50% if the disease establishes itself before tasselling stage. Yield losses ranging from 30 to68% have been reported (Freymark *et al.*, 1993). The symptoms include cigarette-shaped lesions on the lower leaves. Entire leaves are killed, as if damaged by frost. As the disease progresses, it may spread to husks as well. Breeding resistant hybrids is necessary to minimise the disease, as fungicides are expensive. The fungus overwinters as mycelia on maize residues left on the soil surface. The spores are carried by wind or free water, to cause infection. Lesions develop within 7-12 days of infection.

2.10 Developments in popcorn breeding

2.10.1 History and breeding progress

Popcorn breeding in the USA reportedly started during the 1920s and the focus then was development of inbred lines (Brunson, 1937). The first popcorn breeders existed prior to the discovery of America in 1492. They were American Indian tribes from South and Central America. When popcorn was commercialized around 1890, only open-pollinated varieties were available. The shift from open-pollinated varieties to hybrids resulted in higher yields and improved disease resistance, standing ability and popping quality. The first commercial hybrid was released in Minnesota, USA, in 1934. It was a single cross between two inbred lines from the Japanese Hulless variety and had white kernels. The hybrid was named Minhybrid 250 (Ziegler, 2001).

The germplasm used currently in breeding programmes is sourced from the International Maize and Wheat Improvement Centre (CIMMYT) in Mexico, the National Seed Storage Laboratory in Fort Collins, Colorado, and the North Central Regional Plant Introduction

Centre in Iowa (Sleper and Poehlman, 2006). Popping quality (reviewed above) and yield are very important traits in popcorn. The most important factor that affects yield is genotype. Quality improvement is considered the most important objective in popcorn breeding. The breeding of popcorn is not given as much attention as dent maize.

In South Africa, the only record of popcorn breeding efforts dates back to 1954 (Josephson *et al.*, 1954). It also progresses more slowly than that of dent maize, because breeders need to consider additional quality traits unique to popcorn, e.g. popping expansion, freedom from hulls, and overall texture of flakes (Ziegler, 2001). The slow progress in popcorn breeding is a paradox and contrast with the economic value of the crop (Sakın *et al.*, 2005). Popcorn is profitable for kernel producers, for the seed trade as well as for processors. Evidence of popcorn breeding programmes is prominent in developed countries, with the USA leading. However, a few developing countries are involved in popcorn breeding. These countries include Brazil, Argentina, India and Mexico. In Brazil, popcorn breeding began in 1932. The first Brazilian commercial variety was released in 1941, and the emphasis was on mass selection. The progress in popcorn breeding slowed down drastically until the 1980s when a single cross hybrid and a three-way hybrid were released and commercialized (Rangel *et al.*, 2008). India in its future popcorn strategies has prioritized popcorn breeding. It has not produced any hybrids yet and Indian popcorn varieties currently have popping expansion ratios half those of the industry norm. Varieties commonly grown in India are Amber, VL Almora and Pearl (IASRI, 2009). In Africa, there is mention of popcorn breeding programmes in Nigeria, due to the growing demand for popcorn. These programmes are, however, still incipient (Iken and Amusa, 2010).

2.10.2 Breeding methods and strategies applicable to popcorn

The breeding strategies applicable to dent maize are also applicable to popcorn. The first step is to collect germplasm from different sources. It is critical that source populations consist of desirable genes to contribute towards the attainment of breeding objectives. As stated earlier, in the case of popcorn, both agronomic traits and popping quality are important. It is necessary that source populations are subjected to environmental stresses, to assist in the selection of superior genotypes.

Maize is a cross-pollinated crop. Cross-pollination preserves and promotes heterozygosity in a population. Cross-pollinated crops like maize show mild to severe inbreeding depression and a considerable amount of heterosis (Singh, 1993). Breeding methods applicable to cross-pollinated crops differ from those applicable to self-pollinated crops. When breeding cross-pollinated crops like maize, the heterozygous nature of the crop is exploited (Sleper and Poehlman, 2006). Each plant has both homozygous and heterozygous loci. There is an almost limitless number of possible gene recombination. Due to extensive heterozygosity, cultivars of cross-pollinated plants are less uniform. There is a vast degree of phenotypic variation. When breeding cross-pollinated crops, emphasis is given to inheritance of quantitative traits.

Recurrent selection

The objective of recurrent selection is to increase the frequency of desired alleles, especially for quantitative traits, through repeated cycles of selection. The cycle involves the identification of superior genotypes from a source population and subsequent inter-mating of these genotypes to produce new gene combinations with improved expression of the trait (Sleper and Poehlman, 2006). A number of plants with desirable phenotype are selected and self-pollinated. In the second year, separate progeny rows are grown from seeds obtained from selected plants. Progenies are then crossed. Seed resulting from crosses are composited to produce the next generation. Recurrent selection is useful in improving specific combining ability (Singh, 1993). Recurrent selection is important in the provision of genetic gain for popping expansion (Daros *et al.*, 2002).

Mass selection

Mass selection is one of the earliest breeding methods. It involves visual selection of desirable traits. Mass selection is highly efficient for improving traits that can easily be visually identified, e.g. plant height, ear size, kernel colour, lodging resistance, or date of maturity. During mass selection, plants are selected only on the basis of phenotype and no progeny tests are conducted (Singh, 1993). Seeds harvested from selected plants are bulked to produce the next generation. With mass selection, new cultivars can be developed quickly and there is continuous improvement of traits. The major weakness about mass selection is that the pollen source cannot be controlled. The selection of traits with low heritability is ineffective, because it cannot be distinguished whether plants that are selected are superior due to environmental influences or whether they are genetically superior. Quantitative traits that are easily improved by mass selection are also affected by the environment. To overcome this, a procedure known as gridding may be used to reduce errors in selection. Mass selection has been used successfully in the past and is still effective to improve the yield of maize. Mass selection has been used successfully to improve popping expansion in popcorn (Pereira and Amaral Junior do, 2001; Vivela *et al.*, 2008).

Pedigree selection

In this method, individual plants are selected from F_2 and subsequent segregating generations. The progenies are tested. Throughout the process, a detailed record of progenies and the parents is maintained. This is known as a pedigree record. The pedigree is the description of ancestors for some generations into the past. The pedigree is useful to determine individuals with a common parent. Advantages of pedigree selection lie in the fact that inferior genotypes are discarded early, each generation is exposed to different environments and the genetic relatedness of lines is known. According to Viana (2009), pedigree selection is predominantly used to develop popcorn inbred lines. He further mentions the efficiency of this selection method in the development of superior inbred lines.

Backcross breeding

Backcrossing is used to transfer a specific gene from one genotype to the other, or to improve certain quantitative traits of inbred lines. Backcross breeding is a special form of pedigree breeding. A backcross occurs when an F_1 hybrid is crossed to one of its parents. The result of backcrossing is that the genotype becomes increasingly similar to that of the parent. This method is very popular for improving qualitative traits such as disease resistance. In this method, a hybrid of interest is crossed with one of its parents to increase the dose of desirable genes. This method has been used extensively in popcorn breeding, especially to improve popping characteristics after an inbred line is crossed with dent maize to introduce disease resistance. The repeated backcrossing leads to an increase in homozygosity. Backcross breeding has been successfully used to identify trait-improving quantitative trait loci (QTLs) in popcorn backcrossed to dent maize (Li *et al.*, 2009). It is also useful when disease resistance is introduced to susceptible popcorn lines. Backcross breeding has been applied in popcorn to produce varieties with improved yield and disease resistance (Pereira and Amaral Junior do, 2001).

2.11 Popcorn breeding populations

A population is a group of plants that are mating with each other. Unlike inbred lines and hybrids, each plant in a population has a unique set of genes, which is genetically different from other plants in a population. Open-pollinated varieties and synthetics are examples of populations (Russell and Sandall, 2012). Breeding materials for popcorn exist in the form of inbred lines, open-pollinated varieties (OPVs), synthetics and hybrids.

2.11.1 Inbred lines

Inbred lines are nearly homozygous lines produced through several generations of self-pollination. In maize, inbred lines are preferred over OPVs in the generation of hybrids, because inbred lines can be maintained without change of genotype. The genetic makeup of OPVs is highly unstable and is likely to be altered by evolutionary forces (Singh, 1993). In popcorn, inbred lines are very important in the production of hybrids. Examples include BP3, a yellow popcorn inbred line developed in Iowa, characterized by high popping expansions, and BPM2 is popular for producing tillers and 90% mushroom flakes. It is a good source for developing hybrids with a high percentage of mushroom flakes (Committee for Agricultural Development, 2010)

2.11.2 Open-pollinated varieties

Open-pollinated varieties (OPVs) are a product of uncontrolled pollination. Seed from the previous crop is saved to produce the next crop. The majority of popcorn OPVs were developed prior to 1934, before the release of the first hybrid Minhybrid 250. Popular popcorn OPVs which contributed to hybrids being used today are Japanese Hulless, White Rice, Queen's Golden, Spanish, Superb and Tom Thumb (Ziegler, 2001). Bass *et al.* (2001) refers to Tom Thumb as a useful popcorn even in the present day (Bass *et al.*, 2001). It was used in the breeding by programme of the Florida State University in 2001, to produce an extra-early popcorn variety. In Africa, a few open-pollinated varieties, which include Medao, Grace and Mercy were produced by the Institute of Agricultural Research and Training in Nigeria. Some of these were among varieties evaluated for field disease and vertebrate pest incidence in Nigeria (Amusa *et al.*, 2005). These were also evaluated for consumer acceptability in Nigeria (Iken and Amusa, 2010).

2.11.3 Synthetic varieties

Synthetic varieties are produced by crossing a selection of lines with good combining ability. Ziegler (2001) describes the breeding of synthetic varieties. They are of great value when controlled pollination is a challenge. Inbred lines and OPVs may be used to produce synthetics. A synthetic variety is maintained by open-pollination in isolation. Synthetic varieties are produced by mixing seeds from parental lines in equal parts and planting them in isolation. They are subjected to open-pollination and are expected to produce crosses in all combinations. Seeds are then bulked to produce the next generation. The second way of producing synthetic varieties is to select lines and cross them in all possible combinations in isolation. Equal amounts of seed from each cross are composited to produce a synthetic variety. Synthetic varieties play an important role in popcorn breeding programmes. By 2001, 21 synthetic varieties had been produced through popcorn breeding programmes at Purdue University, Iowa State University and the University of Nebraska in the USA. The synthetic BSP9SGC0 is yellow-kernelled and is used to produce inbred lines with high popping expansion and good agronomic traits. It was released by Iowa State University in 2004. Synthetics HXPD-1 and HPXD-2 were released by Purdue University for improved popping expansion (Ziegler, 2001).

2.11.4 Hybrid varieties

Hybrid varieties are first generations (F_1) from crosses of inbred lines, open-pollinated varieties and other hybrids. In maize, most hybrid varieties are produced from inbred lines. The performance of hybrids is highly dependent on the performance of parents in terms of general combining ability (GCA) and specific combining ability (SCA) (Singh, 1993). Inbred lines need to be tested for GCA and SCA, to identify productive combinations of inbred lines to produce hybrids (Sleper and Poehlman, 2006). Hybrids in maize and popcorn breeding are utilized to improve yields, standing ability, popping expansion and other quality traits. Hybrids are the most important tool to exploit heterosis (Singh, 1993). Maize and popcorn hybrids are characterized by uniform appearance of plants, vigour, high yield, improved grain and improved resistance to biotic and abiotic stress. Hybrids are categorized into single-cross hybrids, double-cross hybrids, three-way hybrids and top-cross hybrids.

Single-cross hybrids - These are produced by crossing two homozygous inbred lines.

Double-cross hybrids - When double-cross hybrids are produced, parents are two single-cross hybrids. Initially, inbred lines are crossed single-cross hybrids which are further crossed to produce a double-cross hybrid.

Three-way hybrids – The parents of a three-way hybrid are a single-cross hybrid and an inbred line.

Top-cross – One of the parents of a top-cross is an open-pollinated variety and the other parent may be a single-cross hybrid or an inbred line. One of the major uses of top-cross hybrids is to estimate the GCA of the line crossed with the OPV (Singh, 1993).

In popcorn, there is wide utilization of hybrids. The first popcorn hybrid was released in 1934. Most hybrids are developed in the USA through breeding programmes conducted at Purdue University, Iowa State University and the University of Nebraska (Ziegler, 2001). Some of these hybrids, including Purdue 3, Purdue 31, Purdue 32 and Purdue 38, were evaluated for yield in South Africa between 1952 and 1954 (Josephson *et al.*, 1954). There is currently one standard hybrid available in South Africa, P618, which is marketed by Capstone Seeds. It is described by the marketer as having large yellow grains (57 kernels per 10g), butterfly type, high-yielding, full-season variety, maturing in 112 days and with the average popping fold of 44. It is susceptible to leaf streak disease like other popcorn varieties. The average yield of this hybrid is estimated at 6 t/ha (Capstone Seeds, 2006). The hybrid is regarded as the industry standard in South Africa and has been used in breeding programmes as a check (Amusa *et al.*, 2005; Trindade *et al.*, 2010). P618 is a North American hybrid (Rangel *et al.*, 2008).

2.12 Gene action

Genes or units of inheritance interact in a variety of ways to influence the phenotype (Qwabe, 2012). Genes express themselves phenotypically, either additively or non-additively. Gene action can therefore be broadly classified into additive and non-additive gene action. Traits governed by non-additive gene action are difficult to fix through selection. In popcorn, quality and agronomic traits are important. It thus becomes important to understand the nature of gene action conditioning these traits. Irshad-Ul-Haq *et al.* (2010) reported both additive and non-additive gene action for plant height, days to mid-pollination and grain yield in maize. Viana and Matta (2003) reported dominance for stem lodging and number of ears per plant.

Genes control the development of characters of traits by interacting with other genes and the environment. Genes occur on chromosomes, either in dominant or recessive form. Alternate forms of the same gene in a locus are called alleles. Types of characters controlled by genes are broadly classified into morphological or structural characters, physiological characters (those that deal with assimilation of nutrients and stress resistance) and as pathological characters which concern with disease resistance (Sleper and Poehlman, 2006). The inheritance of qualitative and qualitative traits occurs in different ways. Quantitative traits or metric traits are controlled by many genes. These genes are also known as minor genes. The effect of a single gene in quantitative inheritance is usually too small to be recognized. The sum of all effects contributed by all genes is measured. Quantitative traits include yield, plant height, seed size and other traits. The inheritance of quantitative traits is affected by environment (Singh *et al.*, 1997; Sleper and Poehlman, 2006). A good example is that yield, a quantitative trait is easily affected by temperature, soil fertility, soil moisture and other environmental factors. Quantitative traits that are highly heritable occur as a result of additive gene action. Those that are slowly heritable are primarily influenced by non-additive gene action. Quantitative traits are also known as polygenic traits, because their inheritance is controlled by many genes.

The inheritance of qualitative traits is governed by one or a few genes with large, easily detectable effects. It is for this reason the genes that control inheritance of qualitative traits are also known as oligogenes. Examples of qualitative traits are disease resistance and flower colour.

Different types of gene action are recognized namely additive gene action, dominance, epistasis and overdominance.

Additive gene action refers to a situation where a gene enhances the expression of the trait. The effect of a single gene adds one increment of the trait, two genes add two units of the trait, e.g. aabb=0, Aabb=1, AAbb=2, AABb=3, AABB=4. This type of gene action affects inheritance of quantitative traits (Singh, 1993).

Dominance is the relationship between two alleles at the same locus, in which one allele masks the expression of the other. Dominance hypothesis suggests that at each locus the dominant allele has a favourable effect, while the recessive allele has a non-favourable effect. In a heterozygote the undesirable effects of recessive alleles are masked by dominant alleles. The heterozygote resembles one parent more than the other. Dominance occurs as complete dominance or partial dominance. With complete dominance, the heterozygote and one homozygote have equal effects, e.g. aa=0, Aa=2, AA=2. In this case, the phenotype of the heterozygote is similar to that of the dominant homozygote.

Partial or incomplete dominance occurs when the phenotype of the heterozygote is distinct and often intermediate to that of the dominant homozygote and the recessive homozygote. Co-dominance, a rare type of partial dominance, occurs when the contribution of both the recessive allele and the dominant allele are visible in the phenotype.

Overdominance occurs when each allele contributes a separate effect. Combined alleles contribute a greater effect than when they occur individually. This is the concept of non-activity. With overdominance, heterozygotes are superior to homozygotes.

Epistasis is a result of non-allelic gene interactions. Epistasis is a form of non-additive gene action. The genes reside on different loci. Two genes have no effect individually, but they have an effect when combined. When gene A and gene B are present together, the effect of B cannot be seen because of the masking effect of A. The alternative form of a trait occurs when both genes are recessive. Epistasis is thought to have an important role in heterosis. Examples of epistasis may be additive x additive, additive x dominance, dominance x dominance x dominance.

2.13 Inbreeding depression and heterosis

Inbreeding depression refers to a severe reduction in fertility and vigour due to inbreeding. Inbreeding is mating between individuals that are closely related. Self-pollination is the process of pollinating a plant with its own pollen. It is a form of inbreeding commonly used in maize breeding. Inbreeding reduces the proportion of heterozygotes and increases the proportion of homozygotes (Singh, 1993). In each generation of self-pollination, heterozygosity is reduced by half. As a result of inbreeding, desirable traits can be fixed due to reduced variation, except when it comes from environmental interactions. Self-pollination has advantages, in that it leads to increased homozygosity. Plants retain their true phenotype from generation to generation. It also leads to decreased segregation. The main disadvantage is linked to inbreeding depression, which occurs after many generations of self-pollination. Inbreeding in cross-pollinated crops leads to a decline in vigour and productiveness, known as inbreeding depression (Sleper and Poehlman, 2006). Popcorn, like all forms of maize, is normally cross-pollinated. Pollen is dispersed by the wind. During pollination, both the tassel and the female inflorescence need to be covered to prevent contamination. Many popcorn inbred lines produced from segregating populations have been successfully developed using this method. In popcorn, inbreeding may result in low yields, which in turn affect popping quality. It has been reported that small kernels associated with poor yield fail to pop effectively and hence adversely affect the quality of the final product (Song *et al.*, 1991). Effects of inbreeding depression were observed in a study by Vivela *et al.* (2008) in the form of decreased unhusked ear diameter and length after repeated mass selection.

To combat inbreeding depression, crossing is used to introduce hybrid vigour or heterosis for yield, disease and pest resistance, standing ability and popping quality. Heterosis, or hybrid vigour is a concept that been exploited extensively in commercial plant breeding. Heterosis is manifested in hybrids and represents superiority in performance of hybrids compared with their parents (Hallauer, 2001). Heterosis is more evident following crosses among diverse genotypes (Sleper and Poehlman, 2006). For a hybrid to be useful, it has to perform better than its parents. Otherwise it has no value for the farmer. In general, cross-pollinated crops show heterosis, especially when inbred lines are used as parents. Heterosis has been commercially exploited in crops like sunflower, maize, onion and lucerne (Singh, 1993). Heterosis is manifested by the hybrid if superior to its parents in terms of yield, growth rate, disease and insect resistance, quality and general vigour. The increase in yield due to heterosis is of great importance and is the most important objective of plant breeding. Increased fertility or productive ability is also important, as it leads to higher yields. Better adaptability of hybrids to different environments is a major contribution of heterosis. Some hybrids show greater resistance to pests and diseases than their parents, as well as earlier maturity and increased vigour.

2.14 Combining ability

Combining ability refers to the ability of a parent to produce offspring or progenies that are superior or inferior when combined with another parent. Good combining ability results in superior progenies, while poor combining ability results in inferior progenies. Combining ability is divided into general combining ability (GCA) and specific combining ability (SCA). According to Hallauer (2010), GCA effects are an indicator for additive gene action, while SCA effects depict non-additive gene action. Traits that are dominated by GCA can be fixed easily through selection. In popcorn and dent maize, traits reported to be governed by both GCA and SCA include NCLB and grain yield, as reported by Derera *et al.* (2007) for maize and by Vijayabharathi *et al.* (2009b) for popcorn. General combining ability is the overall performance of the line when crossed with other lines. General combining ability is evaluated by testing all lines against a common parent, which is known as a tester. Specific combining ability is the contribution of an inbred line to hybrid performance in a cross with a specific inbred line.

2.15 Diallel analysis and its applicability to popcorn breeding

Diallel analysis is used to test combining ability (Borojevic, 1990; Viana and Matta, 2003). The number of possible crosses in a diallel mating design is n (n-1), including reciprocals. In a situation where there are 20 lines, the possible number of crosses is 190. The two approaches to diallel cross analysis are Hayman's graphical approach and Griffing's numerical approach. Griffing's numerical approach to the diallel is used to estimate GCA and SCA effects. Griffing's methodology is the most frequently used, because it is easy to understand and interpret (Viana and Matta, 2003). The analysis of GCA allows identification of superior parents to be used in breeding programmes. The GCA component is a function of additive gene effects. The SCA is a function of dominance (Singh, 1993). Full diallel or partial diallel analysis can be applied when analysing gene action. With partial diallel analysis, it is possible to evaluate a large number of parents at the same time.

2.16 Line x Tester Analysis

The line x tester analysis is a good approach for screening genetic material in terms of GCA and SCA, because the lines with high utility in crosses are targeted in a hybrid-orientated breeding programme. GCA can be due to lines or testers. The SCA effects result from the lines and testers interacting together. It is possible to analyse superior lines and testers by looking at their GCA. The possible number of crosses is equal to the number of lines multiplied by the number of testers. The total number of crosses made is equal to the product of the number of lines. This mating design is useful when the number of lines and testers is not balanced (Singh, 1993).

2.17 Heritability and inheritance of agronomic and quality traits in popcorn

Heritability is the degree to which quantitative characters are transmitted to the progeny (Sleper and Poehlman, 2006). It is the proportion of phenotype that is due to genotype. The other portion is contributed by environmental factors. In plant breeding, it is only genetic variation that is transmitted to the next generation. If the genetic variation is higher than that of environmental variation, then the trait is highly heritable. If the genetic variation is small in respect to environmental variation, the heritability of the trait is low. Genetic variance is categorized into additive variance, dominance variance and epistatic variance in case of non-allelic interactions. Heritability is measured in terms of heritability estimates using analysis of variance or parent-offspring regression (Singh, 1993). In popcorn, yield has been found to have low heritability because it is highly influenced by environmental factors (Sleper and Poehlman, 2006). Popping expansion volume, despite being quantitative, has been reported to have high heritability estimates. Heritability estimates ranging between 0.62 and 0.96 have been observed for this trait in popcorn (Ziegler, 2001). Babu *et al.* (2006) reported a heritability estimate of 0.72 for popping expansion volume. Another trait which shows high heritability estimates is plant height (Li *et al.*, 2008). Daros *et al.* (2002) reported heritability estimate of 0.77 for ear height and 57.48 for grain yield.

Most economically important traits in popcorn are quantitative in nature. They are controlled by many genes and are influenced by environmental factors. Agronomic traits include yield and its secondary components namely prolificacy, plant height, standing ability, ear length, ear position, ear diameter, shelling percentage, days to mid-silking, days to mid-anthesis and disease resistance (Singh, 1993; Sleper and Poehlman, 2006). Quality traits in popcorn include popping expansion volume, popping expansion ratio and number of unpopped kernels. Babu *et al.* (2006) reported that popping expansion volume is a distinct inheritable trait, which is quantitatively inherited.

Yield is a complex trait, controlled by many genes and is the final result of the plant's life-cycle. Yield is a quantitative trait, which is therefore highly affected by effects of the environment. Yield has low heritability values due to effect of the environment. In experiments, grain yield (GY) is used as an indicator of yield. Grain yield is shelled grain weight per plot, adjusted for grain moisture and converted to tons per hectare. It was reported that both additive and non-additive actions were important in the control yield in maize (Derera *et al.*, 2007; Irshad-Ul-Haq *et al.*, 2010; Sibiya *et al.*, 2011). In terms of inheritance of yield in popcorn, similar findings were reported (Scapim *et al.*, 2006; Miranda *et al.*, 2008; Viana *et al.*, 2011). Pereira and Amaral Júnior (2001) also reported overdominance gene action for yield. Plant height is controlled by non-additive gene action (Ulloa *et al.*, 2010). NCLB resistance is reported to be controlled by both additive and non-additive gene action (Welz and Geiger, 2000; Vieira *et al.*, 2009; Sibiya *et al.*, 2011).

2.18 Genotype by environment interaction

In plant breeding, the effects of genotype by environment (GxE) interaction are very important, because every cultivar has inherent capacity to respond to changes of location (Scapim *et al.*, 2010). The process of developing new cultivars takes a long time and thus genetic material is exposed to environmental factors for a number of years. Yield is an important trait affected by genotype by environment interaction and thus has been reported to have low heritability (Li *et al.*, 2007a). Environments differ in terms of light, moisture and soil fertility. In sub-Saharan Africa, the concept of genotype by environment interaction is especially important since maize-growing environments in this region are characterized by both temporal and seasonal fluctuations of weather patterns (Machida, 2008). Three types of genotype by environment interaction are recognized namely cultivar by location interaction, cultivar by year interaction and cultivar by location by year interaction. In popcorn, GxE interactions can include cultivar by popping method interaction since it has been reported that the popping method has an effect on popping (Dofing *et al.*, 1990).

Genotype by environment interaction plays an important role in the inheritance of quantitative traits. These traits are affected significantly by the environment. The result of genotype by environment interaction is that the relationship between genotype and phenotype is hidden. The phenotype does not reveal the genotype. The effect of the environment is not heritable and cannot be passed between generations. It is therefore important for the breeder to know the extent of environmental influence on the quantitative trait. Only the genetic component of variability can be transmitted to the next generation. The extent to which the genotype contributes to the phenotype is expressed as heritability. When a character is highly heritable, it is easy to select for it due to a small contribution of the environment to the phenotype. When a character shows a low heritability value of about 0.4, selection becomes difficult due to the masking effect of the environment. The effect of environmental interaction can be quantified using analysis of variance (Singh, 1993).

2.19 Relationships among agronomic and quality traits in popcorn

During popcorn breeding, relationships between traits have been investigated because they are important in breeding to combine different desirable agronomic traits and popping quality. Phenotypic and genotypic correlations have been determined. Phenotypic correlation includes both genetic and environmental effects. Vijayabharathi *et al.* (2009a) reported a positive correlation between popping expansion volume and popping expansion ratio, negative correlation between ear length and popping expansion ratio and also between grain yield and popping expansion ratio.

2.20 Conclusion

Popcorn is widely consumed all over the world and this therefore has economically important multiplier effects for the second economy. Despite the increasing consumption and popularity of popcorn, it is not produced sufficiently in Africa, due to lack of adapted varieties.

This calls for breeding programmes to develop adapted varieties with good popping quality and agronomic traits. Breeding programmes of this nature need to be aimed at increasing the economic, food value and utilization of the crop in Africa. Developed countries like the USA have successfully developed hybrids adapted to their environment through selection and cross-breeding. Stress-prone environments that characterize Africa can benefit immensely by applying similar breeding strategies. Agronomic traits and popping traits are important in popcorn and they are conditioned by either additive gene action, non-additive gene action, or both. Traits that are governed predominantly by additive gene action are associated with high heritability and can be fixed using traditional breeding strategies like selection. GxE has a role to play in popcorn breeding. Certain traits can be affected more than others by these effects. Relationships exist among traits that can be exploited to enhance breeding programmes. Both agronomic and quality traits can be improved by exploiting these relationships.

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ASSESSMENT OF INBRED LINES FOR POPPING ABILITY

Abstract

Inbred lines form an integral part of maize breeding programmes. In popcorn breeding, lines which combine good popping ability and high yield are desired. For evaluation of popping ability,128 inbred lines and the check hybrid P618 were grown at Ukulinga Research Farm in Pietermaritzburg, South Africa (altitude 812 m, latitude 29.66^0S; longitude 30.40^0E), in November 2010, under standard cultural practices for maize. Evaluation of popping was performed using the microwave method at the University of KwaZulu-Natal, Pietermaritzburg, in June 2011. Quantitative data was analyzed using the SAS statistical package. Variability among inbred lines was statistically significant ($P<0.05$) for number of kernels per 10g, flake volume, number of unpopped kernels and popping fold. Variability among inbred lines for grain moisture content was non-significant ($P<0.05$). Flake volume ranged from 63 cm^3 to 850 cm^3, popping fold ranged from 2.5 to 34 times the original volume. The number of unpopped kernels ranged between 8 and 236. Number of kernels per 10 grams ranged from 45 to 157. Moisture content ranged from 10.3% to 14.9%. The line DPL 116 gave the highest flake volume of 850 $cm^{3.}$ The check hybrid P618 ranked 23rd in terms of flake volume (412.5 cm^3) and popping fold (16.5). DPL 116 had the lowest number (8) of unpopped kernels. DPL 37 had the smallest number of kernels per 10 grams (45), while DPL 88 had the largest number of kernels per 10 grams (157). Kernel size had a significantly ($P<0.05$) positive correlation ($r=0.49$) with number of unpopped kernels. There was a significantly strong and negative correlation ($r= -0.62$) between flake volume and number of unpopped kernels. Correlation was not significant for flake volume and popping fold with the number of kernels per 10 grams (kernel size) and grain moisture content. Overall, the study indicated observations of germplasm lines with high utility for use in breeding hybrids.

3.1 Introduction

Inbred lines are used extensively in the production of maize hybrids (Aslam and Khan, 1985). In popcorn breeding, it is the objective of the breeder to have inbred lines with high yielding potential, together with good popping ability, which is constituted by high popping volume and low number of unpopped kernels. Quality and yield are important traits in popcorn (Sakın *et al.*, 2005). Inbred lines with a good combination of agronomic and popping quality traits are desirable as parents for superior hybrids.

Inbred lines are described as homozygous breeding lines which are developed and maintained by self-pollination. The process of inbred line development starts with heterozygous plants. The heterozygous plants may be selected from a base segregating population, usually acquired from gene banks around the world, or from a population improved through recurrent selection (Sleper and Poehlman, 2006). Self-pollination is advantageous, in that it leads to increased homozygosity; plants retain their true phenotype from one generation to the next. It also leads to decreased segregation. In maize breeding, five to seven generations of self-pollination and pedigree selection are required to achieve homozygosity. Heterozygosity decreases by half for each generation of self-pollination (Singh, 1993). As a result of inbreeding, desirable traits can be fixed due to reduced variation, except that which comes from environmental interactions. The main disadvantage of repeated self-pollination is linked to inbreeding depression, which occurs after many generations of self-pollination. Inbreeding in cross-pollinated crops leads to a decline in vigour and productiveness. Most vigor is lost during early generations of self-pollination (Sleper, 2006).

It is common in crops like popcorn to use backcross breeding during inbred line development to improve certain traits. Backcrossing is used to transfer a specific gene from one genotype to the other, or to improve certain quantitative traits of inbred lines. A backcross occurs when an F_1 hybrid is crossed to one of its parents. The result of backcrossing is that the genotype becomes increasingly similar to that of the parent. This method is very popular for improving quantitative traits like disease resistance. With this procedure, a hybrid of interest is crossed with one of its parents to increase the dose of desirable genes. This method has been used extensively in popcorn breeding, especially to improve popping characteristics after an inbred line is crossed with dent maize or flint maize to introduce disease resistance. Backcross breeding has been successfully used by Li *et al.* (2009) in popcorn backcrossed to dent maize. Superior inbred lines are extremely important in plant breeding, as they are utilized to develop superior hybrids.

Inbred lines are preferred over open-pollinated varieties in the generation of hybrids, because inbreds can be maintained without change of genotype (Singh, 1993). According to Viana (2009) pedigree selection is predominantly used to develop popcorn inbred lines. He further mentioned the efficiency of this selection method in the development of superior inbred lines. Examples of important inbred lines include BP3, a yellow popcorn inbred line developed in Iowa, characterized by high popping expansions. The line BPM2 is popular for producing tillers and 90% mushroom flakes.

The objectives of the study were:

a) To determine variability of inbred lines for popping ability and associated traits
b) To determine heritability for popping quality traits
c) To determine relationships among popping quality traits in popcorn inbred lines.

3.2 Materials and methods

3.2.1 Germplasm background

Three sets of maize germplasm were utilized and are classified as Set A, Set B and Set C. The first set (A) of germplasm was constituted by segregating landrace popcorn base populations obtained from CIMMYT in Mexico. The base population is equivalent to an F_2 segregating population. The breeding materials were subjected to eight generations of self-pollination with selection (pedigree breeding) in a shuttle programme at Makhathini Research Station, Ukulinga Research Farm and Cedara Research Station, until the F_{10} seed generation was obtained. The research stations are located within the province of KwaZulu-Natal. The breeding process is illustrated in the following schematic diagram:

Year	**Generation**	**Process**
2007B	F_2	F_2 (S_0) equivalent seed obtained from CIMMYT
2008A	F_3	Self-pollination and selection at Ukulinga
2008B	F_4	Self-pollination and selection at Makhathini
2009A	F_5	Self-pollination and selection at Ukulinga
2009B	F_6	Self-pollination and selection at Makhathini
2010A	F_7	Self-pollination and selection at Ukulinga
2010B	F_8	Self-pollination and selection at Makhathini
2011A	F_9	Self-pollination and selection at Cedara
2011B	F_{10}	S8 seed bulking at Makhathini

The popcorn breeding process with the second set (B) towards the development of inbred lines commenced in summer 2008 at the Ukulinga Research Farm by self-pollination of F_2 popcorn grain from the market to produce the F_3 families. This base germplasm was designated as the local breeding population. It was discovered that local F_3 popcorn families were susceptible to NCLB. This necessitated improvement of the population for resistance to the disease. For introgression of NCLB resistance genes, an F_3 family used as a susceptible male parent (P_1) was crossed to a resistant flint maize parent (P_2). Since crosses with normal maize lead to loss of popping ability, a backcross breeding programme was applied to generate BC_1 populations. The BC_1 populations were self-pollinated for four generations, between 2009 and 2011, to fix the genes as outlined:

Year	**Generation**	**Process**
2008B	F_2	Local F_2 populations obtained
2008B	F_3	Self-pollination and selection
2009A	F_{2} (P_1) x Flint (P_2)	Cross to introgress NCLB resistance genes
2009B	BC_1F_1	Self-pollination and selection
2010A	BC_1F_2	Self-pollination and selection
2010B	BC_1F_3	Self-pollination and selection
2011A	BC_1F_4	Self-pollination and selection
2011B	BC_1F_4	Bulking of seed at Makhathini

The third set (C) of germplasm was developed from local progenies equivalent to F_2 popcorn grain from the market. These materials were subjected to eight generations of self-pollination and selection, as follows:

Year	Generation	Process
2008B	F_2	F_2 grain obtained locally from the market
2008B	F_3	Self-pollination and selection at Makhathini
2009A	F_4	Self-pollination and selection at Ukulinga
2009B	F_5	Self-pollination and selection at Makhathini
2010B	F_6	Self-pollination and selection at Makhathini
2011A	F_7	Self-pollination and selection at Cedara
2011B	F_8	Self-pollination and selection at Makhathini

3.2.2 Seed production and management

To bulk the seed for use in the laboratory popping tests, a total of 128 inbred lines from three sets, developed in the manner described above, were grown at Ukulinga Research Farm (altitude 812 m, Latitude 29.66^{0}S; longitude 30.40^{0}E). The trial was planted in November 2010. The fertilizer 2:3:4(NPK) was applied at the rate of 150 kg/ ha at planting. Topdressing was done at 6 weeks by applying LAN (28) at the rate of 150kg/ ha. Standard cultural practices for maize production were applied, including hand planting, hand weeding, the use of herbicides and insecticides. The trial site was rain-fed, with occasional supplementary irrigation. Pollination was facilitated through self-pollination and full-sib mating.

3.2.2 Laboratory evaluation of popping

Popping experiments were performed using the microwave method on 128 inbred lines and the standard check P618 at the University of KwaZulu-Natal, Pietermaritzburg, in June 2011. The moisture content of each sample was measured in two replicates, using the Dole® grain moisture tester. Kernel size was determined by measuring 10 gram samples in two replicates and then counting the number of kernels per 10 grams. The kernels were classified into small, medium and large. Popcorn kernels are classified by size as follows:

52-67 large, 68-75 medium, 76-105 small (Song *et al.*, 1991; Singh *et al.*, 1997; Allred-Coyle *et al.*, 2000). Samples for popping were measured in duplicate, each with a volume of 25 cm^3 and placed in brown paper bags. Microwave popping was performed using a 700W LG model MF1924 microwave oven, with 24 litre capacity and power of 230V. The samples were popped for three minutes. Flake volume was measured using a 2000 cm^3 measuring cylinder tapped once to settle the popcorn flakes. The number of unpopped kernels was counted and recorded. Popping fold on a volume by volume basis was calculated, by dividing the flake volume by the original volume (25 cm^3) of unpopped kernels.

3.3 Data analysis

Data was analyzed using PROC GLM procedure in the SAS statistical package. Analysis of variance (ANOVA) was done to determine differences among inbred lines. Means were compared by Duncan multiple range test (DMRT). Variance component analysis was performed, using REML tool in GenStat. Heritability estimates were done according to the equation VG/VP, where VG = genetic variance and VP = phenotypic variance. Heritability estimates were done according to the equation VG/VP, where VG = genetic variance and VP = phenotypic variance. They were categorized according to Robinson *et al.* (1949), as follows: 0-30%: Low, 30-60%: Moderate and >60%: high.

3.4 Results

3.4.1 Variability among inbred lines for quality traits

The analysis of variance results showing variability among inbred lines, are presented in Table 3.1. Results indicate that variability among inbred lines was highly significant ($P \leq 0.01$) for number of kernels per 10 g, which depicts kernel size, flake volume, number of unpopped kernels and popping fold. Variation in terms of moisture content was non-significant.

Table 3. 1: Analysis of variance for 128 popcorn inbred lines at Ukulinga Research Farm

Source	**Kernels per 10g**		**Moisture Content**		**Flake Volume**		**Unpopped kernels**		**Popping Fold**	
	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F
Rep	3.11	0.812	0.0		209.9	0.905	89.3	0.7878	0.34	0.905
Entry	683.6	<.0001	0.607	<0.001	38340.5	<.0001	4010.4	<.0001	61.3	<.0001
H^2	0.92		0.99		0.62		0.70		0.62	
R^2	0.93		0.50		0.73		0.77		0.73	
CV (%)	7.85		0.60		22.0		29.3		22.0	
Minimum	45.0		10.3		62.5		8.0		2.5	
Mean	94.0		13.6		276.5		119.6		11.1	
Maximum	157.0		14.9		850.0		236.0		34.0	

H^2 means heritability in a broad sense, DF for Rep = 1 and Entry = 127

Flake volume ranged from 62.5 cm^3 to 850 cm^3 and popping fold from 2.5 to 34. The number of unpopped kernels varied between 8 and 236. Number of kernels per 10 grams ranged from 45 to 157. Moisture content was from 10.3% to 14.9%. The means of popping quality traits of inbred lines are presented in Table 3.3 and Appendix 3. The line DPL 116 gave the highest flake volume, of 850 cm^3. Line DPL 80 gave the lowest flake volume, of 62.5 cm^3. In terms of popping fold the two lines gave the highest and lowest values, popping 34 and 2.5 times the original volume of 25 cm^3, respectively. The check P618 ranked 23rd in terms of flake volume (412.5 cm^3) and popping fold (16.5). DPL 116 had the lowest number of unpopped kernels and DPL 48 had the highest number of unpopped kernels. The values were 8 and 236, respectively. DPL 37 had 45 kernels per 10 grams, which was the smallest number, while DPL 88 had the largest number, 157 kernels per 10 grams. DPL 68 had the lowest moisture content of 10.3%. DPL 16 had the highest moisture content, at 13.6%.

Table 3. 2: Means for popping quality traits in the top 20 and bottom 5 popcorn inbred lines

Rank	**Entry**	**Line**	**Kernels per 10g**	**Moisture Content**	**Flake Volume**	**Unpopped Kernels**	**Popping Fold**
1	116	DPL116	85.0	13.5	850.0	8.5	34.0
2	117	DPL117	94.0	13.3	655.0	39.5	26.2
3	56	DPL56	126.5	12.9	650.0	31.5	26.0
4	7	DPL7	82.5	13.3	587.5	93.5	23.5
5	89	DPL89	120.0	13.0	565.0	62.5	22.6
6	31	DPL31	87.0	13.3	512.5	56.0	20.5
7	131	DPL131	88.5	13.0	512.5	90.5	20.5
8	3	DPL3	101.0	12.8	500.0	48.5	20.0
9	16	DPL16	89.5	13.6	500.0	119.0	20.0
10	47	DPL47	74.5	13.2	500.0	49.0	20.0
11	54	DPL54	120.0	12.8	500.0	84.0	20.0
12	129	DPL129	88.0	13.2	500.0	78.5	20.0
13	94	DPL94	81.0	13.1	487.5	30.0	19.5
14	99	DPL99	94.0	12.8	475.0	54.5	19.0
15	2	DPL2	84.0	12.9	462.5	65.0	18.5
16	127	DPL127	89.0	12.9	450.0	95.0	18.0
17	1	DPL1	74.0	12.8	437.5	45.5	17.5
18	53	DPL53	105.0	13.0	437.5	98.5	17.5
19	135	DPL135	79.0	13.4	430.0	104.0	17.2
20	90	DPL90	90.0	13.0	425.0	106.0	17.0
			Bottom Five Inbred Lines				
124	87	DPL87	93	11.0	112.5	149.0	4.5
125	112	DPL112	113	13.4	90.0	144.0	3.6
126	35	DPL35	71	13.1	75.0	105.5	3.0
127	36	DPL36	57	13.1	75.0	77.0	3.0
128	80	DPL80	81	10.8	62.5	128.0	2.5
Mean			94	14.9	276.5	119.6	23.5
LSD			14.6	0.15	239.7	34.9	9.6

The frequency (%) distribution histogram for the 128 popcorn inbred lines (Figure 3.1) indicates that the majority of kernels were in the small category. The frequency histogram on Figure 3.2 indicates that the most common flake volume for the 128 inbred lines ranged from 101 to 200 cm^3.

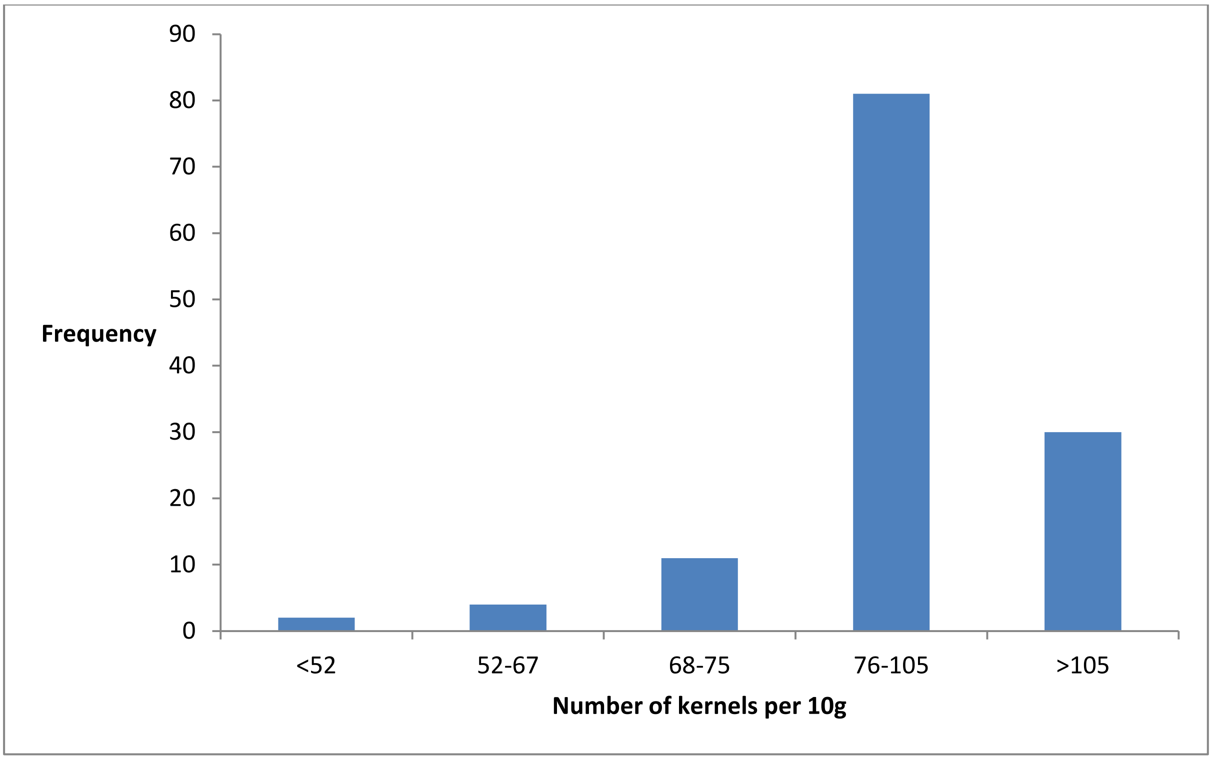

Figure 3. 1: Frequency distribution of kernel size for inbred lines

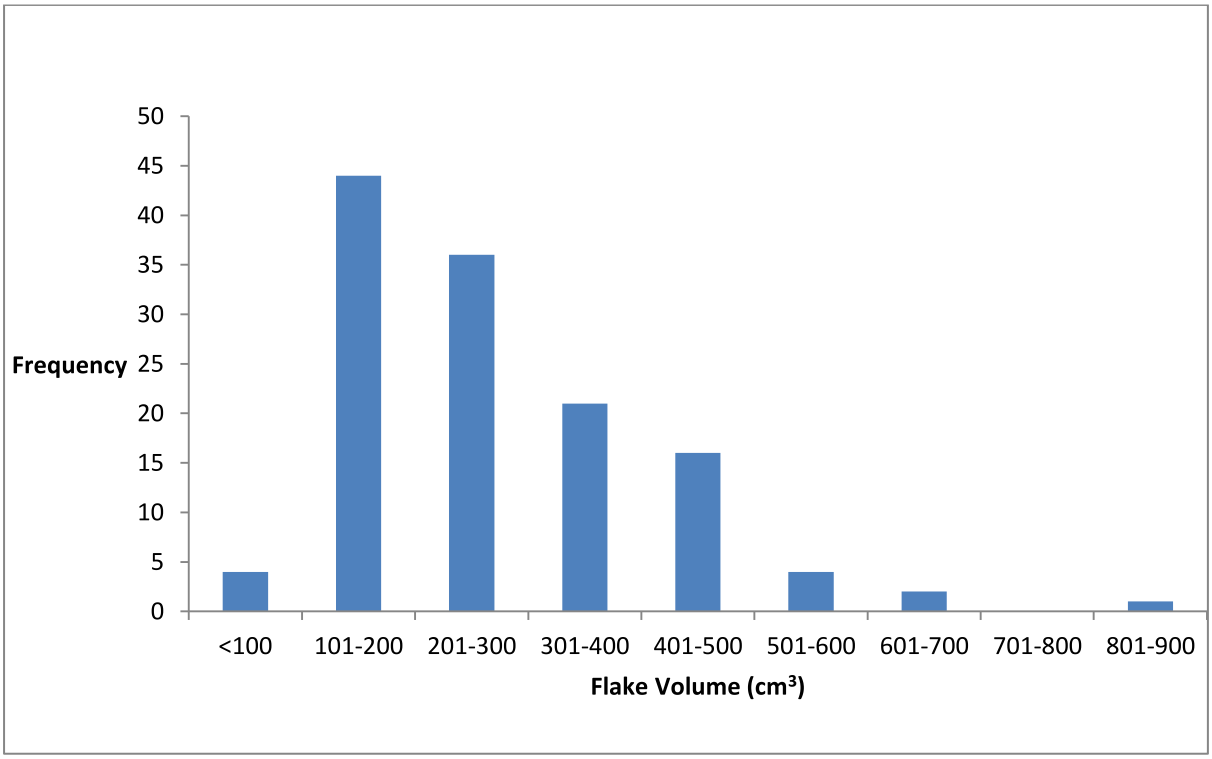

Figure 3. 2: Frequency distribution of flake volume for inbred lines

3.4.2 Heritability of popping quality traits

Heritability estimates for popping quality traits are shown in Table 3.1 for the traits: flake volume (62%), popping fold (62%), number of kernels per 10 grams (92%), moisture content (0.99) and number of unpopped kernels (70%).

3.4.3 Relationships among popping quality traits

Relationships among popping quality traits are presented in Table 3.3. Kernel size had a significant positive correlation (r=0.49) with number of unpopped kernels. Results indicate a significant perfect correlation (r=1) for flake volume with popping fold. There was a significant strong and negative correlation (r= -0.62) between flake volume and number of unpopped kernels. Correlation was not significant for flake volume and popping fold with number of kernels per 10 grams (kernel size) and moisture content.

Table 3. 3: Phenotypic correlations among popping quality traits of 128 inbred lines

	Kernels per 10g	**Moisture Content**	**Flake Volume**	**Unpopped Kernels**	**Popping Fold**
Variable					
Kernels per 10g					
Moisture Content	-0.08				
Flake Volume	0.04	-0.01			
Unpopped Kernels	0.49**	-0.02	-0.62**		
Popping Fold	0.04	-0.01	1.00**	-0.62**	1.00

**,* = r value significant at P≤0.01 and P≤0.05, respectively.

3.5 Discussion

3.5.1 Variability among inbred lines for quality traits

The study revealed significant variability among inbred lines for flake volume, popping fold, number of unpopped kernels and kernel size. Significant differences among genotypes for flake volume, popping fold, number of unpopped kernels and kernel size agree with previous studies (Song *et al.*, 1991; Oz and Kapar, 2011). This indicates the possibility of identifying suitable inbred lines for these quality traits. The line DPL 116 gave the highest flake volume of 850 cm^3.The popping fold of the line DPL 116 was 34. Significant variability in terms of kernel size indicates that lines can be identified for different types of consumers. Home consumers prefer small kernels, because they produce tender flakes with less conspicuous hulls, while vendors prefer medium to large kernels, because they do not break easily during handling (Ziegler, 2001). Heritability values of all traits were high, indicating the possibility for effective selection. High heritability values for these traits were reported in previous studies (Lu *et al.*, 2003; Babu *et al.*, 2006; Li *et al.*, 2007b).

3.5.2 Relationships among popping quality traits

The significant ($P<0.05$) negative correlation between flake volume and number of unpopped kernels is consistent with previous studies (Babu *et al.*, 2006). This indicates that the flake volume decreases as the number of unpopped kernels increases. Unpopped kernels fail to contribute to flake volume and hence are unrealized profit to the consumer. It is thus important to select popcorn varieties which produce minimum unpopped kernels. Significant positive correlation between flake volume and popping fold concurs with the study by Babu *et al.*, (2006). Significant ($P<0.05$) positive correlation was observed between kernel size and number of unpopped kernels. Non-significant correlation between kernel size and flake volume was in contrast to previous studies (Dofing *et al.*, 1990; Singh *et al.*, 1997). In these studies, significant ($P<0.05$) positive correlations were observed.

3.6 Conclusion

Several conclusions could be drawn from the study.

Results indicated that inbred lines were significantly different for flake volume, popping fold, kernel size and number of unpopped kernels. Twenty-two inbred lines performed better than the standard check P618 in terms of flake volume, popping fold and the number of unpopped kernels. There were no significant differences among inbred lines for grain moisture content. This indicates that grain moisture content of inbred lines at the time of popping was not significantly different. It could be concluded that inbred lines with superior popping ability could be developed with the potential to be used as parents for developing hybrids.

Heritability was high for all traits, ranging from 62 to 99%, indicating that selection for popping ability would be effective.

The study also indicates a significant correlation between flake volume and popping fold. A significant negative correlation was observed between flake volume and number of unpopped kernels, indicating that both traits would show the same level of popping ability of genotypes. Therefore breeders can measure only one of these two parameters to reduce research costs. The relationships between popping ability and secondary traits would be exploited during selection. Kernel size had a significant positive correlation with number of unpopped kernels, indicating that genotypes with large kernels are likely to be dent or ordinary flint maize grain and could be discarded during selection.

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Assessment of agronomic traits in popcorn hybrids

Abstract

Popcorn is becoming increasingly popular as a snack and is consumed all over the world. However, adequate production is hampered by lack of adapted varieties. A total of 119 experimental hybrids were evaluated at Cedara Research Station and Ukulinga Research Farm in the province of KwaZulu-Natal in South Africa, during the summer 2011/2012 season. Single cross hybrids were developed from 87 inbred lines, following a breeding programme involving three sets of germplasm, between 2007 and 2011. The crosses between inbred lines were made at random in 2010 to develop the 119 experimental hybrids. The commercial hybrid P618 was used as the check. Agronomic traits measured were grain yield, ear length, plant height, days to mid-pollination, ear position, shelling percentage, stem lodging and NCLB. Data were analyzed using the SAS statistical package. Hybrids were significantly different for all agronomic traits. Means for grain yield ranged from 1.0 t/ha to 5.2 t/ha. The hybrid 11POPH20 gave the highest yield at 5.2 t/ha. The check hybrid P618 gave the mean yield of 2.9 t/ha. GCA effects were highly significant for ear length, plant height, ear position, number of ears per plant, stem lodging and grain yield, suggesting that additive gene action governs the conditioning of these traits. SCA effects were significant for ear length, number of ears per plant and yield, indicating that non-additive gene effects were influential for these traits. Grain yield showed significant and positive correlation with ear length, plant height, ear position, shelling percentage and number of ears per plant. There was significant weak and negative correlation between grain yield and NCLB, also between grain yield and stem lodging. Site effects were highly significant for NCLB, ear length, days to mid-pollination, ear position, number of ears per plant and stem lodging. Site by line interaction effects were non-significant for all traits. Site by tester interaction effects were significant for shelling percentage and non-significant for all other traits. Site by line by tester interaction effects were significant for plant height and non-significant for all other traits. The study was able to identify hybrids with reasonable yield, which require further testing, provided they meet the popping ability threshold.

4.1 Introduction

In popcorn, yield is important, even though it is not a primary trait for selection. The majority of popcorn hybrids available on the market were bred in the USA and show poor adaptability in the stress-prone environments of southern Africa. Quality and yield are important in popcorn (Sakın *et al.*, 2005). There are numerous challenges threatening the economic production of popcorn in developing countries, since it is inferior to dent maize in yield and other agronomic traits (Babu *et al.*, 2006). Planting of varieties that are not adapted to stress-prone environments in Sub-Saharan Africa, leads to major crop failures in the region.

Popcorn is a challenging crop to grow due to poor agronomic traits, including weak and thin stems, which promote susceptibility to root and stem lodging (Trindade *et al.*, 2010). Standing ability is an important trait in popcorn as popcorn needs to remain on a cob much longer than normal maize to reach full maturity. Popcorn is harvested at moisture content between 16 and 18%. Dent maize is ready for harvest at a moisture content of about 20%. The popcorn plant must remain standing even after the stem has begun to deteriorate. Poor standing ability has a negative effect, since it prevents crop maturity, leading to low yields. The high ear placement and weak stalks make it prone to lodging (Ziegler, 2003; Li *et al.*, 2006). Leaf diseases including northern corn leaf blight (NCLB) can cause great losses. Economically important agronomic traits in popcorn include yield and its secondary components, namely prolificacy, plant height, standing ability, ear length, ear position, ear diameter, shelling percentage, days to mid-silking, days to mid-anthesis and disease resistance. Yield of popcorn hybrids is reported to be two thirds that of dent maize hybrids. Yield is highly affected by genotype (Sakın *et al.*, 2005; Vijayabharathi *et al.*, 2009b) and is a complex trait, controlled by many genes. As a quantitative trait, yield is highly affected by effects of the environment (Oz and Kapar, 2011). Yield has been reported to have low heritability values, due to the effect of the environment (Sleper, 2006).

The understanding of inheritance of agronomic traits in popcorn and relationships among them is crucial in achieving successful breeding programmes. Genotype by environment interaction has an important effect on inheritance of agronomic traits. These traits are affected significantly by the environment. Heritability is defined as the proportion of phenotypic variance which is due to the genotype effects. Knowledge of heritability informs the breeders about the best strategy to improve the traits. For example, a high heritability is desired because it implies that selection would be effective in improving the trait of interest.

The objectives of the study were as follows:

a) To determine variability for yield, its secondary traits and NCLB resistance in popcorn hybrids
b) To determine the nature of gene action for yield, its secondary traits and NCLB resistance in popcorn hybrids
c) To determine relationships between yield, its secondary traits and NCLB resistance in popcorn hybrids
d) To determine the effect of genotype by environment interaction on agronomic traits

4.2 Materials and methods

4.2.1 Germplasm development – random mating

Hybrids were developed from a population of 128 inbred lines. Since there was no prior information about the lines, the bi-parental crosses were generated at random in 2010, depending on synchrony of anthesis and silking dates. All lines were used as male and female in different crosses, depending on the synchronization of flowering. Reciprocal crosses were bulked at harvest. Only 87 inbred lines were involved in the 119 crosses, which produced enough hybrid seed for planting in trials.

4.2.2 Trial design and management

A total of 119 experimental hybrids were planted at the Cedara Research Station (altitude 1066 m, latitude 29.54^{0}S; longitude 30.26^{0}E) and the Ukulinga Research Farm (altitude 812 m, latitude 29.66^{0}S; longitude 30.40^{0}E) during 2011/2012 summer season. The commercial hybrid P618 was used as the check. Experiments were laid in a 10x12 alpha lattice design, with two replications at each site. Each experimental plot consisted of a single row 5 m long. Plants were spaced 30 cm apart within the rows and 90 cm between the rows. The trials were planted on 22 November 2011 at Ukulinga Research Farm and on 1 December 2011 at Cedara Research Station. The fertilizer 2:3:4(30) was applied at the rate of 150 kg/ha at planting. Topdressing was done at six weeks, by applying LAN (28) at the rate of 150 kg/ha. Standard cultural practices were applied; including hand planting, hand weeding, use of herbicides and insecticides. Trials at both sites were rain fed, with occasional supplementary irrigation.

The following traits were recorded at both sites:

- Plant height – measured in cm as height from the base of the plant to the insertion of the first tassel branch of the same plant.
- Ear height – measured in cm as height from the base of the plant to the insertion of the top ear.
- Ear position – a ratio of ear height to plant height.
- Stem lodging – measured as % of plants with stems broken below the ear.
- Root lodging - measured as % of plants with stems inclining by more than $45^{0.}$
- Field weight – the weight in kilograms of all de-husked ears or cobs in the plot.
- Grain yield – shelled grain weight per plot, adjusted to 14% grain moisture and converted to tons per hectare.
- Anthesis date – measured as the number of days after planting, when 50% of the plants shed pollen.
- Silking date - measured as the number of days after planting, when 50% of the plants in the plot have silks 2-3 cm long.
- *E. turcicum* – score of severity of NCLB symptoms, rated on a scale of 1 (no infection) to 5 (severe infection).
- Grain moisture – percentage of moisture of grain measured at harvest.
- EPP – number of ears per plant. Counted as the number of ears divided by the number of harvested plants.
- Ear length – measured in cm from the base to the tip of the ear.

4.2.3 Data Analysis

Data was analyzed using PROC GLM procedure in the SAS statistical package. Analysis of variance (ANOVA) was done to determine differences among hybrids, considering all agronomic traits. The hybrids were partitioned into three elements, namely male and female main effects, and male x female interaction effects. According to Hallauer and Miranda (1988), the male and female main effects represent GCA, whereas their interaction (female x male) indicates SCA effects. A random effects model was followed because crosses were generated at random. The model used for data analysis across sites is as follows:

$Y_{jkl} = \mu + s_j + r_k(s_j) + b(r_k\ s_j) + f + m + mf + fs_j + ms + fms + e_{jkl}$
Where Y_{jkl} = observed hybrid response
μ = overall trial mean
s_j = site main effects
r_k = effect of k^{th} replication
$b(r_k\ s_j)$ = effect of blocks within replications and sites
f = female main effects
m = male main effects
fm = female x male interaction effects
fs = female x site interaction effects
ms = male x site interaction effects
fms = female x male x site interaction effects
e_{jkl} = experimental error.

Contributions of male and female lines to the crosses were estimated by calculating the percentage of their sum of squares relative to the total sum of squares for the crosses. Pearson phenotypic correlation coefficients between traits were performed, using the PROC CORR procedure in SAS. Variance component analysis was, using REML tool in GenStat. Heritability estimates were done according to the equation V_G/V_P, where VG = genetic variance and V_P = phenotypic variance. Means were compared by Duncan multiple range test (DMRT). The heritability values were categorized according to Robinson (Robinson, 1949), as follows: 0-30%: Low, 30-60%: Moderate and >60% High.

4.3 Results

4.3.1 Variability among hybrids for agronomic traits

The analysis of variance results for entry and site effects are presented in Table 4.1. The results indicate that hybrids differed significantly ($P\leq 0.01$) from one another for grain yield, ear length, plant height, days to mid-pollination, ear position, number of ears per plant, stem lodging and NCLB. Hybrids were significantly different ($P\leq 0.05$) for shelling percentage. The performance data of hybrids is presented in Table 4.2. Means for grain yield ranged from 1.0 t/ha to 5.2 t/ha. The hybrid 11POPH20 had the highest yield of 5.2 t/ha which was 80% more than the check hybrid. The check P618 had a mean yield of 2.9 t/ha. The mean yield for the trial was 2.7 t/ha.

Means for yield, its secondary traits and NCLB scores for the top 15 and bottom 5 hybrids are presented in Table 4.2. Means for grain yield ranged from 1 t/ha to 5.2 t/ha. The trial mean for grain yield was 2.7 t/ha. The hybrid 11POPH20 gave the highest yield, at 5.2 t/ha while the hybrid 11POPH100 gave the lowest of 1 t/ha. The check P618 ranked at number 42 in terms of grain yield with a yield of 2.9 t/ha. The highest yielding hybrid 11POPH20 had the NCLB score of 2.4, compared with the check P618, with the NCLB score of 3.3. The lowest yielding hybrid 11POPH100 gave the NCLB score of 3.0.

Table 4. 1: Mean squares for agronomic traits in popcorn hybrids across two sites

Source	**DF**	**NCLB**		**EARL**		**PHT**		**DMP**		**EPO**		**SHELL**		**EPP**		**SL**		**YIELD**	
		MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	104.07	<.0001	120.50	<.0001	910.25	0.0339	310.41	<.0001	0.01	0.0242	0.05	0.0088	0.21	0.0493	109095.06	<.0001	1.21	0.0575
Bloc(Site*Rep)	46	0.30	<.0001	1.71	0.0071	516.98	<.0001	2.51	0.401	0.00	0.2837	0.01	0.0069	0.07	0.1747	492.57	0.0035	0.80	<.0001
Entry	119	0.18	<.0001	8.14	<.0001	771.82	<.0001	7.00	<.0001	0.01	<.0001	0.01	0.0249	0.20	<.0001	625.95	<.0001	1.75	<.0001
Site*Entry	119	0.10	0.4471	1.09	0.3014	238.78	0.1324	3.24	0.031	0.00	0.1782	0.01	0.0977	0.06	0.2016	441.26	0.0018	0.41	0.0879
Error	194	0.10		1.00		199.34		2.39		0.00		0.01		0.05		275.20		0.33	
Heritability Estimate		0.49		0.87		0.73		0.66		0.69		0.20		0.73		0.42		0.74	
R^2		0.90		0.88		0.82		0.80		0.77		0.66		0.79		0.84		0.84	
CV (%)		10.02		5.23		6.17		2.15		8.59		11.75		16.93		65.47		21.42	
Mean		3.09		19.17		228.66		71.93		0.50		0.74		1.37		25.34		2.69	

NCLB, Northern corn leaf blight; EARL, Ear length; PHT, Plant height; DMP, Days to mid-pollination; SHELL, Shelling (%); EPP, Ears/plant; SL, Stem lodging

Table 4. 2: Means and rankings for agronomic traits in popcorn hybrids across two sites

Entry	**Name**	**Yield**			**NCLB**	**EARL**	**PHT**	**DMP**	**EPO**	**SHELL**	**EPP**	**SL**
		% P618	Mean (t/ha)	Rank	(score)	(cm)	(cm)			(%)	No.	(%)
20	11POPH20	180.86	5.2	1	2.4	24.4	270.8	76.0	0.61	0.74	1.6	1.7
96	11POPH96	146.55	4.3	2	3.0	17.6	239.5	72.8	0.55	0.77	1.7	17.7
105	11POPH105	139.48	4.0	3	3.0	19.4	239.0	74.8	0.53	0.74	1.7	44.6
108	11POPH108	137.07	4.0	4	2.4	19.1	238.0	76.0	0.57	0.75	1.7	54.4
30	11POPH30	135.00	3.9	5	3.0	21.6	227.0	70.0	0.51	0.72	1.5	28.9
99	11POPH99	132.24	3.8	6	2.9	20.6	229.0	70.8	0.53	0.73	1.6	34.8
111	11POPH111	131.03	3.8	7	2.9	19.2	224.5	72.8	0.53	0.78	1.7	13.5
83	11POPH83	129.66	3.8	8	3.1	21.3	236.5	72.8	0.51	0.73	1.4	16.7
9	11POPH9	125.60	3.6	9	3.0	18.9	239.8	71.8	0.59	0.76	1.8	52.7
76	11POPH76	125.17	3.6	10	3.1	19.9	236.3	70.3	0.48	0.74	1.7	17.6
109	11POPH109	122.67	3.6	11	2.6	18.2	242.3	71.3	0.57	0.65	1.7	34.7
68	11POPH68	122.50	3.6	12	2.6	21.2	236.0	71.0	0.45	0.66	1.4	12.3
92	11POPH92	121.81	3.5	13	2.9	18.0	248.8	71.3	0.57	0.75	1.8	47.1
102	11POPH102	120.60	3.5	14	2.8	19.3	256.3	73.3	0.51	0.76	1.7	47.9
60	11POPH60	119.66	3.5	15	3.4	20.3	229.3	72.5	0.49	0.74	1.7	28.3
120	**P618**	**100.00**	**2.9**	**42**	**3.3**	**20.1**	**233.0**	**71.3**	**0.48**	**0.74**	**1.3**	**43.8**
32	11POPH32	53.53	1.6	116	3.3	18.4	217.8	71.5	0.41	0.70	1.2	32.0
16	11POPH16	52.67	1.5	117	3.4	16.3	195.8	71.8	0.45	0.73	1.1	54.2
12	11POPH12	50.60	1.5	118	2.8	19.2	219.3	72.3	0.46	0.74	1.3	20.8
117	11POPH117	50.43	1.5	119	3.1	18.8	241.0	72.5	0.50	0.72	1.3	21.3
100	11POPH100	33.97	1.0	120	3.0	17.4	191.8	76.0	0.51	0.70	1.2	39.6
LSD			**0.96**		**0.90**	**1.69**	**22.63**	**2.67**	**0.06**	**0.12**	**0.34**	**37.18**

NCLB, Northern corn leaf blight; EARL, Ear length; PHT, Plant height; DMP, Days to mid-pollination; SHELL, Shelling (%); EPP, Ears/plant; SL, Stem lodging

4.3.2 Gene Action

The mode of gene action for agronomic traits, as depicted by GCA and SCA, is presented in Table 4.3. The proportion of GCA and SCA for agronomic traits is shown in Table 4.4. GCA was highly significant for ear length, plant height, ear position, and number of ears per plant, stem lodging and grain yield but not significant for NCLB and shelling percentage. GCA contributed by males was highly significant for all traits. SCA was highly significant for ear length, plant height, number of ears per plant and grain yield. It was not significant for NCLB, days to mid-pollination, shelling percentage and stem lodging.

Heritability estimates are shown in Table 4.1 and were as follows: DMP (66%), EARL (87%), EPO (69%), EPP (73%), GY (74%), NCLB (49%), PHT (73%), SHELL (20%), SL (42%).

Table 4. 3: Mean squares for GCA and SCA for agronomic traits in popcorn hybrids across two sites

	df	**NCLB**		**EARL**		**PHT**		**DMP**		**EPO**		**SHELL**		**EPP**		**SL**		**Yield**	
Source		MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	82.85	<.0001	90.11	<.0001	656.31	0.0738	194.17	<.0001	0.0146	0.0054	0.0406	0.0228	0.380	0.0085	83037.48	<.0001	1.06	0.0754
Blk(Site*Rep)	46	0.30	<.0001	1.73	0.0064	508.49	<.0001	2.37	0.5203	0.0020	0.3141	0.0130	0.0079	0.069	0.1236	499.76	0.0035	0.82	<.0001
Female	47	0.13	0.0703	8.94	<.0001	843.89	<.0001	6.65	<.0001	0.0040	0.0001	0.0106	0.073	0.127	<.0001	597.67	0.0002	1.50	<.0001
Male	44	0.20	0.0006	3.99	<.0001	522.97	<.0001	4.35	0.0039	0.0040	0.0002	0.0109	0.0617	0.197	<.0001	679.10	<.0001	1.72	<.0001
Female*male	20	0.08	0.6707	2.79	0.0002	421.11	0.0062	3.62	0.0872	0.0021	0.3176	0.0074	0.514	0.091	0.0371	399.18	0.1112	0.73	0.003
Site*female	47	0.06	0.9509	1.08	0.3675	214.16	0.39	2.60	0.3586	0.0021	0.2515	0.0113	0.0398	0.052	0.5246	391.42	0.0586	0.38	0.2601
Site*male	44	0.09	0.6333	0.98	0.5314	210.09	0.4229	3.49	0.0501	0.0015	0.8001	0.0128	0.0109	0.054	0.4548	358.56	0.1272	0.37	0.2887
Site*female*male	20	0.13	0.1426	1.32	0.1765	348.70	0.0334	2.51	0.4193	0.0023	0.2184	0.0052	0.8425	0.064	0.2652	319.33	0.3065	0.45	0.1509
Error		0.10		1.01		203.00		2.42		0.0018		0.0077		0.054		278.65		0.33	
R^2		0.90		0.88		0.82		0.80		0.77		0.66		0.79		0.84		0.84	
CV (%)		10.11		5.24		6.23		2.16		8.65		11.85		16.94		66.28		21.41	
Mean		3.09		19.16		228.62		71.94		0.50		0.74		1.37		25.18		2.69	

NCLB, Northern corn leaf blight; EARL, Ear length; PHT, Plant height; DMP, Days to mid -pollination; SHELL, Shelling (%); EPP, Ears/plant; SL, Stem lodging

Table 4. 4: Proportion (%) of GCA and SCA for agronomic traits estimated based on sum of squares.

Variable	**GCA**			**SCA**
	Line	**Male**	**Total**	
Northern corn leaf blight	37.84	52.41	90.25	9.75
Ear length	64.46	26.98	91.44	8.56
Plant height	55.79	32.37	88.15	11.85
Days to mid-pollination	54.24	33.21	87.44	12.56
Ear position	46.42	43.27	89.68	10.32
Shelling percentage	44.27	42.56	86.82	13.18
Number of ears per plant	36.30	52.65	88.96	11.04
Stem lodging	42.59	45.30	87.90	12.10
Grain yield	43.74	47.14	90.88	9.12

4.3.3 Relationships among agronomic traits

Correlation coefficients were significant (P≤0.05) for NCLB with ear length, days to mid-pollination, ear position, stem lodging and grain yield (Table 4.5). There was no significant correlation for NCLB and plant height, shelling percentage and number of ears per plant. Positive and strong correlation was observed for NCLB with stem lodging (r= 0.57). There was weak negative correlation between NCLB and days to mid-pollination (r= -0.32), ear position (r= -0.15) and grain yield (r= -0.19). Significant correlation of ear length was found with plant height, stem lodging and grain yield. Correlation was significant for plant height with ear position, shelling percentage, number of ears per plant, stem lodging and grain yield. Significant correlation was observed between shelling percentage and grain yield. Significant correlation of number of ears per plant was found with grain yield. Correlation was significant, weak and negative between stem lodging and grain yield (r= -0.21).

Table 4. 5: Phenotypic correlations for yield, yield components and NCLB in popcorn hybrids

Variable	NCLB	EARL	PH	DMP	EPO	SHELL	EPP	SL	GY
NCLB									
EARL	-0.26**								
PH	-0.08	0.28**							
DMP	-0.32**	0.06	-0.09						
EPO	-0.15**	0.02	0.20**	0.23**					
SHELL	0.00	-0.03	-0.12*	0.08	0.00				
EPP	-0.06	0.01	0.32**	0.05	0.30**	-0.002			
SL	0.57**	-0.32**	-0.10*	-0.12*	-0.01	0.006	-0.01		
GY	-0.19**	0.35**	0.45**	-0.07	0.27**	0.19**	0.53**	-0.21**	1

**,* = r value significant at P≤0.01 and P≤0.05, respectively. NCLB = Northern Corn Leaf Blight; EARL = ear length; PH = plant height; DMP = days to mid-pollination; EPO = ear position; SHELL = shelling percentage; EPP = number of ears per plant; SL = stem lodging; GY = grain yield

4.3.4 Genotype x environment interaction effects on agronomic traits

Results depicting genotype x environment interaction are shown in Table 4.1 and Table 4.3. Site effects were highly significant for NCLB, ear length, days to mid-pollination, ear position, number of ears per plant and stem lodging. Site effects were not significant for plant height, shelling percentage and grain yield. Entry by site interaction effects were highly significant (P≤ 0.01) for stem lodging. They were significant (P≤ 0.05) for days to mid-pollination. They were non-significant for NCLB disease, ear length, plant height, ear position, shelling percentage, number of ears per plant and grain yield. Site by line interaction effects were non-significant for all traits. Site by male interaction effects were significant for shelling percentage and non-significant for all other traits. Site by line by male interaction effects were significant for plant height and non-significant for all other traits.

4.4 Discussion

4.4.1 Variability among hybrids for agronomic traits

The study showed that hybrids were significantly different for grain yield and yield components across sites. There was significant variability for ear length, plant height, days to mid-pollination, ear position, shelling percentage, number of ears per plant, stem lodging and grain yield. Hybrids were also significantly different for NCLB disease. This indicates an opportunity to select hybrids that are suitable for different environments in terms of yield and NCLB disease resistance. The results showing significant variation of hybrids for agronomic traits agree with previous studies involving popcorn hybrids (Sakın *et al.*, 2005; Moterle *et al.*, 2012). The hybrid POPH20 yielded 81% more than the check. In terms of popping ability, the same hybrid ranked among the bottom five. These results concur with previous studies that grain yield is negatively correlated to popping expansion volume. The check P618 ranked at number 42 in terms of grain yield. Ear length was also variable. The hybrid 11POPH20, which was the highest-yielding, had the highest ear length. Plant height ranged from 191.8 cm (POPH100) to 270.8 cm (POPH20). Days to mid-pollination ranged from 69 to 76. Ear position ranged from 0.40 to 0.61. The minimum shelling percentage was 0.53. The lowest number of ears per plant was 0.8 and the highest was 1.9. This indicates that none of the hybrids were barren. Each of the 119 experimental hybrids had an ability to produce a cob. Stem lodging ranged from 0 to 64.1%. The study indicates that there is still a need to decrease stem lodging. NCLB scores ranged from 2.4 (resistant) to 3.6 (moderately susceptible), implying that the hybrids were moderately resistant or susceptible, because the score of 1 indicates high resistance, while 5 indicates high susceptibility to NCLB disease. The highest yielding hybrid 11POPH20 had the NCLB score of 2.4, compared with the check P618 with the NCLB score of 3.3. The lowest yielding hybrid 11POPH100 gave the NCLB score of 3.0, which was better than the check.

4.4.2 Gene action

The study revealed highly significant GCA and SCA effects for grain yield, ear length, number of ears per plant and plant height. This indicates the importance of both additive and non-additive gene action in the conditioning of these traits. The greater GCA sum of squares for GCA for grain yield (90.88%), ear length (91.44%), plant height (88.15%) and ear position (88.96%) indicate that additive gene action is more important than non-additive gene action for conditioning of these traits. The findings of this study indicating that the importance of additive gene action was more than non-additive gene action for grain yield, concur with previous studies on normal maize (Irshad-Ul-Haq *et al.*, 2010; Sibiya *et al.*, 2011), and on popcorn (Vieira *et al.*, 2011). Pajic´, (2008) reported non-significant GCA for grain yield and ear position in his study involving popcorn. Previous studies on popcorn revealed significant GCA and dominance for stem lodging (Viana and Matta, 2003). GCA effects were predominant over SCA effects for all traits. Only GCA was significant for days to mid-pollination, ear position and stem lodging, which indicates that additive gene action determines the conditioning of these traits. GCA and SCA were not significant for shelling percentage, which indicates the difficulty in selecting for this trait.

Generally, agronomic traits had high heritability values with the exception of NCLB disease, shelling percentage and stem lodging. The results indicate difficulty for selecting for these traits. Other breeding strategies like hybridization would need to be applied. Traits with high heritability values can be improved quicker with and fewer resources.

4.4.3 Relationships among agronomic traits

Grain yield showed significant positive correlation with ear length, plant height, ear position, shelling percentage and number of ears per plant. This is an indication that these secondary traits of yield positively influence grain yield. A high ear position contributes to better light interception by the ear, leading to better yield. The findings of this study in terms of these relationships concur with previous studies (Mani and Dadari, 2003; Golam *et al.*, 2011).

Grain yield showed significant negative correlation with NCLB and stem lodging. This indicates that as NCLB and stem lodging increase, grain yield is affected negatively. NCLB was found to be positively correlated to stem lodging. Plants that are severely infected by NCLB tend to be prone to stem lodging. Grain yield was not significantly correlated with days to mid-pollination, indicating that days to mid-pollination as a trait does not affect yield. The results concur with previous studies (Malik, 2005).

4.4.4 Genotype x environment interaction effects on agronomic traits

The results of the study indicate that site effects were highly significant for NCLB disease, ear length, days to mid-pollination, ear position, number of ears per plant and stem lodging. Site effects were not significant for plant height, shelling percentage and grain yield. The non-significant result for grain yield is an indicator of stability of the experimental hybrids that were produced. Entry by site interaction effects were highly significant ($P \leq 0.01$) for stem lodging. They were significant ($P \leq 0.05$) for days to mid-pollination. They were non-significant for NCLB, ear length, plant height, ear position, shelling percentage, number of ears per plant and grain yield. Significant site by entry interaction effects, in contrast with the results of this study, were previously reported by (Broccoli and Burak, 2004) and (Scapim *et al.*, 2010).

4.5 Conclusion

The objectives of the study were to evaluate variability, gene action, correlations and genotype by environment interaction for agronomic traits in popcorn experimental hybrids. Agronomic traits include yield, its secondary traits and NCLB. Results indicated that there is significant variability for all agronomic traits. This presents an opportunity to select hybrids that are suitable for different environments in terms of yield and NCLB resistance. The hybrid 11POPH20 gave the highest yield which was 81% higher than the check, P618. The check P618 ranked at number 42 in terms of grain yield. Hybrids with better resistance to NCLB disease could be identified.

The study revealed highly significant GCA and SCA effects for grain yield, ear length, number of ears per plant and plant height, indicating the importance of both additive and non-additive gene action, respectively, in governing these traits. GCA effects were predominant over SCA effects for all traits. Only GCA was significant for days to mid-pollination, ear position and stem lodging. GCA and SCA were not significant for shelling percentage, which indicates the difficulty in selecting for this trait. High heritability estimates also support the importance of additive variation for most traits, implying that selection would be effective to improve the popcorn hybrids.

Significant relationships between yield and the secondary traits were observed, with implications for breeding. Grain yield was significantly positively correlated to ear length, plant height, ear position, shelling percentage and number of ears per plant, implying that these traits can be targeted to improve yield through indirect selection. There was significant weak and negative correlation between grain yield and NCLB, as well as between yield and stem lodging, implying that these traits did not have any significant effect on yield. Positive and strong correlation was observed for NCLB with stem lodging, indicating that high disease levels weakened the stems and contributed to lodging.

Genotype x environment interaction was not significant for grain yield, except for a few secondary traits, indicating that the hybrids were generally stable. This partly explains the high heritability which was observed.

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Assessment of popping ability in popcorn hybrids

Abstract

Popcorn forms an important snack food worldwide and is classified as a whole-grain snack, with nutritional benefits including high fibre, low fat and low sodium content. It is also rich in vitamins and minerals. Adequate production is hampered by lack of adapted varieties especially to the stress-prone environments which prevail in Africa. This situation calls for breeding investigations to develop new adapted hybrids. A total of 119 experimental hybrids and the standard check P618 were subjected to popping experiments to evaluate popping quality traits at the University of KwaZulu-Natal, Pietermaritzburg in June 2012. The hybrids and the check P618 were planted at Cedara Research Station and Ukulinga Research Farm in Pietermaritzburg during summer 2011. Two popping methods were used, the microwave method and the hot air popping method. The data was analyzed using the SAS statistical package. The significant variability that was observed in the study among hybrids for popping quality traits presents an opportunity for selection of hybrids with good popping ability. The hybrid 11POPH13 gave the highest flake volume (1288 cm^3) and the highest popping fold (25.75). The check, hybrid P618, had the flake volume of 1156 cm^3 and the popping fold of 23.1 and was ranked 16th for popping ability. Additive gene action was more prominent than non-additive action for all popping quality traits. This creates an opportunity to effectively improve these traits through selection. Relationships among quality traits, as well as among agronomic traits, were established. Flake volume was found to be negatively correlated to grain yield and quality score. The prevalence of NCLB disease compromised popping quality through its influence on quality score and increased the number of unpopped kernels. Generally, genotype x popping method interaction effects on popping ability were negligible, indicating that there could be fewer complications in breeding new varieties.

5.1 Introduction

Popcorn is a special type of flint maize which pops when exposed to heat treatment and produces flakes of different shapes, colour and sizes. The popping ability of popcorn, which makes it unique to other types of maize, is due to the nature of the kernel components, the endosperm and pericarp. Popcorn kernels can be distinguished into two types, the rice type and the pearl type. Varieties with white kernels are usually associated with the rice type of kernel, while pearl types are commercially associated with yellow kernelled popcorns. Size of popcorn kernels is divided into small, medium and large. Studies indicate that consumers prefer popcorn that is tender, fluffy and with a high expansion volume (Allred-Coyle, 2000). The product of popping is called a flake. Flakes differ in size, shape and colour. Park and Maga (2001) reported the existence of yellow and white flakes, and that yellow flakes were preferred from white by the panel of tasters involved in the study. Mushroom-shaped flakes are round with very few wings. The butterfly-shaped flakes are irregular. Butterfly-shaped flakes tend to be tender and are preferred by movie theatres to be sold on the premises. They are also susceptible to breakage and cannot withstand extended handling (Ziegler, 2001).

Expansion volume is the most critical quality factor for popcorn (Borras, 2006). Factors such as kernel size and shape have an impact on expansion volume (Karababa, 2006; Ertas, 2009). Expansion volume is a quality trait of great importance to consumers, as unpopped kernels are sold by weight and popcorn flakes are sold by volume (Shimoni *et al.*, 2002, Allred-Coyle, 2000). Large expansion volumes are associated with tender flakes. Popcorn quality depends on a number of factors. It needs to have a good kernel colour, free from pronounced hulls, have good flavour, tenderness and good popping expansion (Dickerson, 2003). Expansion volume is affected by the percentage or number of unpopped kernels and moisture content at the time of popping. Moisture content at the time of popping should be between 13 and 14.5% (Ziegler, 2001). Studies by Shimoni *et al.* (2002) demonstrated that the moisture content of kernels has an effect on popping temperature. The size is determined by weighing a 10 g sample of kernels and counting the number of kernels per 10 g. Medium-sized kernels appeals to both home consumers and processors. Small kernels are preferred by home consumers because they tend to produce small but tender flakes, with a few hulls. Vendors prefer large flakes for good eye appeal and toughness, so that they do not break easily. There are three popping methods used to produce popcorn flakes, namely oil popping, microwave popping and hot air popping.

The objectives of the study were as follows:

a) To determine variability among hybrids for popping quality traits
b) To determine gene action involved in conditioning of quality traits in popcorn hybrids.
c) To determine relationships among quality traits in popcorn
d) To evaluate the effect of genotype by environment interaction on quality traits
e) To determine the effect of method by genotype interaction for popping ability

5.2 Materials and methods

The hybrids were developed as described in Chapter 4. Popping experiments were performed on 119 experimental hybrids and the standard check P618 at the University of KwaZulu-Natal, Pietermaritzburg, in June 2012. The hybrids and the check P618 had been planted at Cedara and Ukulinga during the summer of 2011. Two popping methods were used, the microwave method and the hot air popping method. Samples were popped in two replicates for each method. The moisture content of each sample at the time of popping was measured in two replicates using the Dole® moisture meter. Kernel size was determined by measuring 10 gram samples in two replicates and then counting the number of kernels per 10 grams. The kernels were classified as small, medium and large. Popcorn kernels are classified by size in the following manner: 52-67 large, 68-75 medium, 76-105 small (Song *et al.*, 1991; Singh *et al.*, 1997; Allred-Coyle *et al.*, 2000).

5.2.1 Evaluation of popping by microwave method

Samples, each with a volume of 25 cm^3, were measured in duplicate and placed in brown paper bags. Microwave popping was performed using a 900W Defy DMO 351 microwave oven, with 28 litre capacity and power of 230V. The samples were popped for three minutes.

5.2.2 Evaluation of popping by hot air method

Samples, each with a volume of 25 cm^3, were measured in duplicate and placed in a hot air popping machine. The Samsung hot air popcorn maker model SPC 900 was used for popping. Popcorn grain samples were popped for two minutes.

5.2.3 Data collection and measurement

Flake volume was measured using a 2000 cm^3 measuring cylinder, tapped once to settle the popcorn flakes. The number of unpopped kernels were counted and recorded for each sample. Popping fold (PF) was calculated by dividing the flake volume by the original volume (25 cm$^{3)}$ of unpopped kernels. The quality score (QS) of popcorn flakes after popping was measured visually on a scale of 1-5 in terms of whiteness and uniformity of flake colour, flake size, uniformity of flake shape (mushroom or butterfly), tenderness and amount of hulls. A score of 1 is best quality and a score of 5 is worst quality.

5.3 Data analysis

Data was analyzed using the PROC GLM procedure in the SAS statistical package. Analysis of variance (ANOVA) was done to determine differences among hybrids, considering all agronomic traits. The hybrids were partitioned into three elements, namely male and female main effects and male x female interaction effects. According to Hallauer and Miranda (1988), the male and female main effects represent GCA, whereas their interaction (female x male) indicates SCA. A random effects model was followed, because crosses were generated at random. The model used for data analysis across sites is as follows:

$Y_{jkl} = \mu + s_j + r_k(s_j) + b(r_k s_j) + f + m + mf + fs_j + ms + fms + e_{jkl}$

Where Y_{jkl} = observed hybrid response

μ = overall trial mean

s_j = site main effects

r_k = effect of kth replication

$b(r_k s_j)$ = effect of blocks within replications and sites

f = female main effects

m = male main effects

fm = female x male interaction effects

fs = female x site interaction effects

ms = male x site interaction effects

fms = female x male x site interaction effects

e_{jkl} = experimental error.

Contributions of male and female lines to the crosses were estimated by calculating the percentage of their sum of squares relative to the total sum of squares for the crosses. Pearson phenotypic correlation coefficients between traits were performed using the PROC CORR procedure in SAS. Variance component analysis was performed using the REML tool in GenStat. Heritability estimates were done according to the equation VG/VP, where VG = genetic variance and VP = phenotypic variance. Means were compared by Duncan multiple range test (DMRT).

5.4 Results

5.4.1 Observations for popping quality

It was observed that timing of popping when using the microwave method was critical. The effects of different popping times are shown in Fig. 5.1.

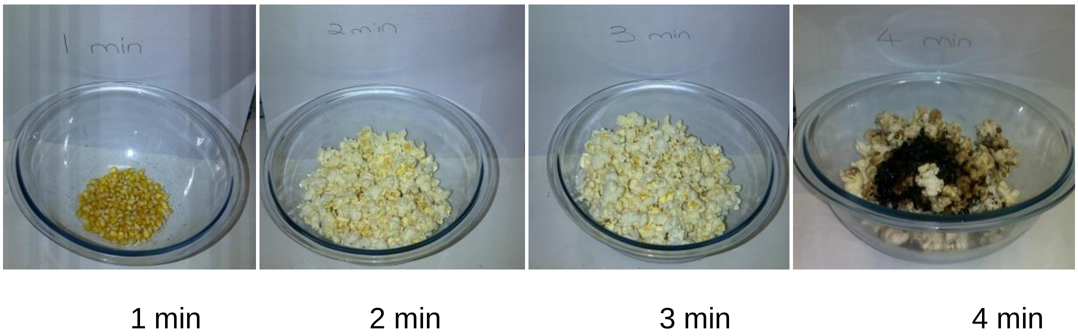

Figure 5. 1: Effect of different popping times on popping ability in the microwave

When different popping times were tested, it was discovered that popping started at 2 minutes. At 1 minute, no popping occurred. At 2 minutes, little popping had occurred and a large number of unpopped kernels were present. At 3.3 minutes, slight burning of samples was observed. At 4 minutes, considerable burning of samples had occurred.

Hybrids which produced a large number of unpopped kernels were observed and the majority of them fell into the small kernel category. Large hulls, which are not desirable, were produced by certain hybrids, as shown in Figure 5.2.

Figure 5. 2: Unpopped kernels and amount of hulls produced by some popcorn hybrids

The quality of popcorn flakes varied among genotypes, as shown in Figure 5.3. The flake colour, when visually observed, varied from white to yellow-brown. The colour of flakes produced by various hybrids was not uniform. Flake shape varied from butterfly (right) to mushroom (left). There were hybrids which produced a mixture of butterfly and mushroom flakes. Large and small flakes were observed.

Figure 5. 3: Variation in popcorn flakes showing flake shape, flake size and flake colour

5.4.2 Variability among hybrids for popping quality traits

The analysis of variance results showing variation among hybrids are presented in Tables 5.1 and 5.2. Results indicate that variation among hybrids was highly significant ($P \leq 0.01$) for all traits except moisture content. There were significant differences among hybrids for flake volume, popping fold, number of unpopped kernels, quality score and number of kernels per 10 g which depicts kernel size. Flake volume across sites and across popping methods varied from 734 cm^3 to 1288 cm^3. Popping fold ranged from 14.69 to 25.75. The number of unpopped kernels was between 19 and 121. Kernel size varied from 49 to 90 kernels per 10 grams. Moisture content was from 12.14 to 27.35 percent. Quality scores ranged from 1.2 to 3.1. The means and ranking for popping quality traits for the top 15 and bottom five hybrids are presented in Table 5.3. In terms of flake volume and popping fold, the hybrid POPH13 gave the highest flake volume (1288 cm^3) and the highest popping fold (25.75). The check, hybrid P618, had a flake volume of 1156 cm^3 and the popping fold of 23.1. The check was ranked 16th for popping ability. The top performing hybrid POPH13 yielded the flake volume which was 11% higher than the check hybrid.

The means for the rest of the hybrids are shown in Appendix 3, while the frequency of the traits for all the hybrids are presented in Figures 5.4 and 5.5.

Table 5. 1: Mean squares for popping quality traits of 120 popcorn hybrids across two sites

		Flake Volume		**Popping Fold**		**Unpopped Kernels**	
Source	**DF**	**MS**	**Pr > F**	**MS**	**Pr > F**	**MS**	**Pr > F**
Site	1	981671.58	<.0001	392.6048	<.0001	74533.941	<.0001
Rep	1	29244.41	0.2649	11.70883	0.2646	67211.799	<.0001
Method	1	1417002.13	<.0001	566.8779	<.0001	198937.86	<.0001
Entry	119	96158.08	<.0001	38.46585	<.0001	3186.7229	<.0001
Site*method	1	35652.39	0.2183	14.2488	0.2185	4792.8031	0.0099
Entry*method	119	21728.85	0.6906	8.692815	0.69	717.8388	0.4766
Site*entry	119	28983.23	0.0649	11.59366	0.0648	835.4975	0.1311
Site*entry*method	119	21078.4	0.7591	8.431487	0.7588	568.7896	0.9344
Error	477	23468.07		9.38619		714.761	
R^2		0.7		0.7		0.7	
CV (%)		14.6		14.6		52.8	
Min		734		14.69		19	
Max		1288		25.75		121	
Mean		1046.516		20.93038		50.66353	

Table 5. 2: Mean squares for moisture content, quality score and kernel size of 120 popcorn hybrids across two sites

Source		**Moisture Content**		**Quality Score**		**Kernels per 10g**	
	DF	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	37.748	0.0223	37.080	<.0001	5916.040	<.0001
Rep	1	9.931	0.2392	0.013	0.8375	21.309	0.4822
Entry	119	7.176	0.4776	0.612	<.0001	337.868	<.0001
Site*entry	119	7.354	0.4165	0.412	0.0333	79.771	<.0001
Error	477	7.132		0.310		43.012	
R^2		0.511		0.683		0.846	
CV (%)		20.671		27.773		9.585	
Min		12.14		1.2		49.0	
Max		27.30		3.1		90.0	
Mean		12.90		2.0		68.0	

Table 5. 3: Means and rankings for popping quality traits for the top 15 and bottom five hybrids

ENTRY	NAME	PEDIGREE	RelFV(%P618)	FV	RANK	PF	UPK	kn10g	MC	QS
13	11POPH13	11MAK 2-11X51	111.35	1287.5	1	25.8	29.1	65.8	13.1	2.2
81	11POPH81	11MAK 2-55X29	108.10	1250.0	2	25.0	47.4	67.1	12.7	1.7
82	11POPH82	11MAK 2-59X49	106.48	1231.3	3	24.6	32.5	65.3	12.9	1.6
24	11POPH24	11MAK 2-20X77	105.40	1218.8	4	24.4	34.1	55.8	13.1	1.3
37	11POPH37	11MAK 2-35X32	105.40	1218.8	6	24.4	47.4	65.3	12.9	2.2
33	11POPH33	11MAK 2-33X5	105.40	1218.8	5	24.4	46.8	64.0	12.6	1.6
21	11POPH21	11MAK 2-18X8	104.86	1212.5	7	24.3	44.8	65.8	12.8	1.5
19	11POPH19	11MAK 2-13X72	103.91	1201.6	8	24.0	35.9	65.4	12.8	1.5
110	11POPH110	11MAK 2-83X48	102.70	1187.5	9	23.8	20.9	60.6	12.9	1.8
43	11POPH43	11MAK 2-38X10	102.43	1184.4	10	23.7	45.5	65.0	13.2	2.2
14	11POPH14	11MAK 2-11X64	101.62	1175.0	11	23.5	51.9	68.6	13.0	1.2
17	11POPH17	11MAK 2-12X62	101.35	1171.9	12	23.4	52.4	66.4	13.0	2.0
117	11POPH117	11MAK 2-71X47	101.35	1171.9	13	23.4	38.7	63.4	12.9	2.0
22	11POPH22	11MAK 2-18X49	101.08	1168.8	14	23.4	55.3	65.4	13.0	1.8
116	11POPH116	11MAK 2-11X36	101.08	1168.8	15	23.4	64.0	72.4	12.9	1.9
120	**P618**	**P618**	**100.00**	**1156.3**	**16**	**23.1**	**53.9**	**64.0**	**13.0**	**1.6**
Bottom Five Hybrids										
23	11POPH23	11MAK 2-19X55	70.54	815.6	116	16.3	24.8	52.1	12.7	1.7
87	11POPH87	11MAK 2-60X50	70.00	809.4	117	16.2	44.9	68.5	12.6	2.7
20	11POPH20	11MAK 2-14X81	65.40	756.3	118	15.1	29.8	50.0	12.8	2.2
108	11POPH108	11MAK 2-81X50	64.86	750.0	119	15.0	29.3	69.0	12.7	2.3
68	11POPH68	11MAK 2-50X22	63.51	734.4	120	14.7	18.8	49.1	12.9	2.3
LSD				**160.02**		**3.20**	**31.83**	**11.83**	**3.70**	**0.93**

PF, popping fold; FV, flake volume; UPK, number of unpopped kernels; MC, grain moisture content; kn10g, number of kernels per 10g of grain; QS, quality score; RelFV, relative to flake volume of control hybrid P618; RANK, rank according to popping ability.

Frequency distribution (%) of kernel size results are shown in Figure 5.4. Results indicate that the majority of hybrids produced large kernels. Out of 120 hybrids including the check, 63 had large kernels, 27 had medium kernels and 28 had small kernels. Two hybrids produced extra-large kernels, with a kernel count of fewer than 52 kernels per 10 grams.

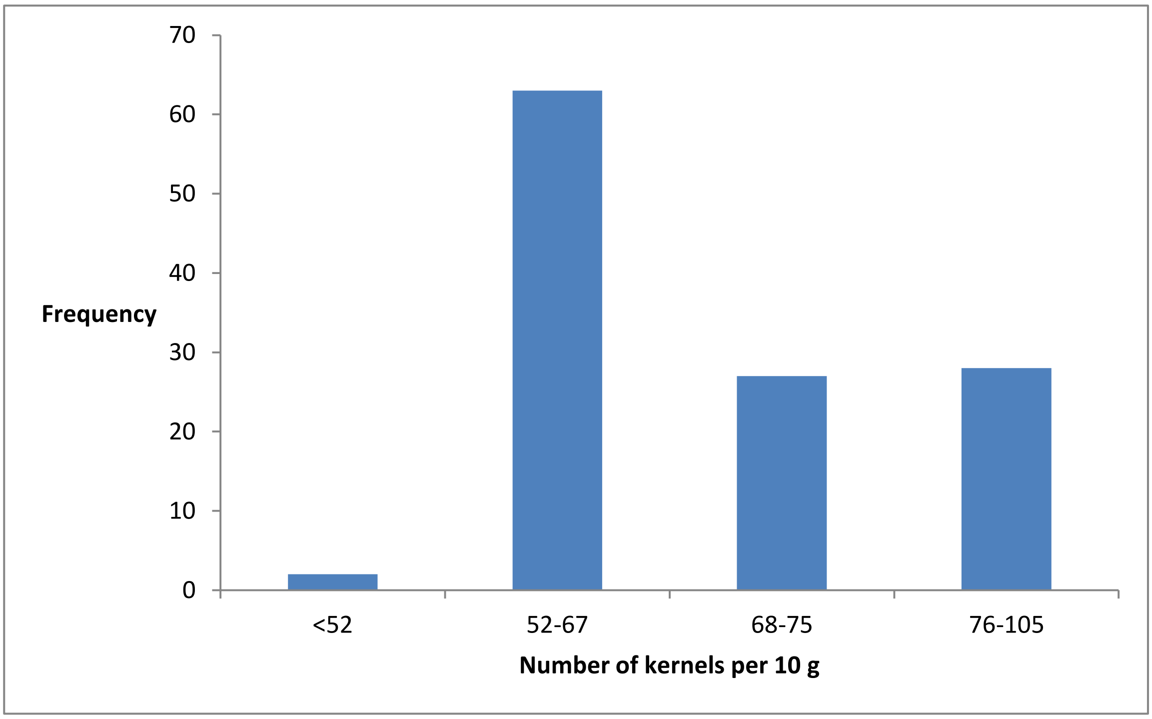

Figure 5. 4: Frequency distribution of kernel size for popcorn hybrids

Frequency distribution (%) of flake volume is shown in Figure 5.5. Results indicate that 3 out of 120 hybrids produced a flake volume ranging from 701 – 800 cm^3; 11 hybrids produced a flake volume of 801-900 cm^3; 26 hybrids produced a flake volume of 901-1000 cm^3; 37 hybrids produced a flake volume of 1001-1100 cm^3; 35 hybrids produced a flake volume of 1101-1200 cm^3 and 8 hybrids produced a flake volume of 1201-1300 cm^3.

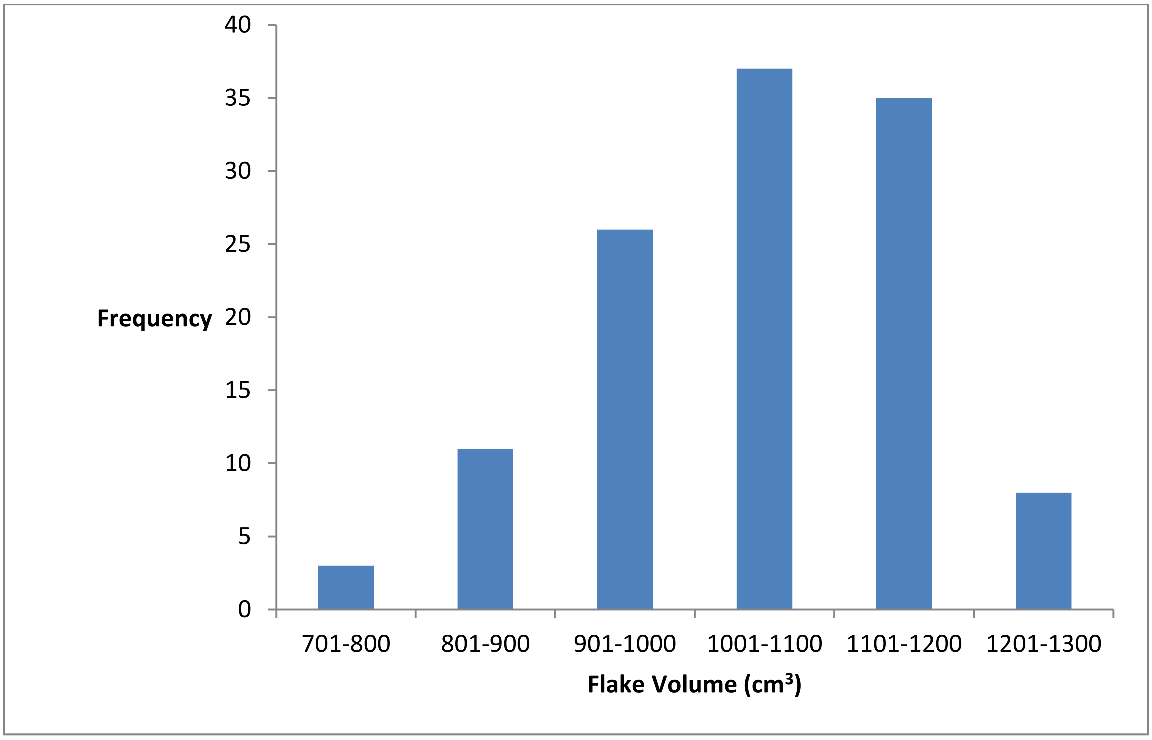

Figure 5. 5: Frequency distribution of flake volume for popcorn hybrids

5.4.3 Genotype x environment interaction effects on popping quality traits

The results in Table 5.4 reveal that site main effects were highly significant for flake volume, popping fold, number of unpopped kernels, quality score and number of kernels per 10 grams. Site effects were not significant for moisture content. Site by entry interaction effects were only significant for the number of unpopped kernels and the quality score. The effect of the popping method was significant for flake volume, popping fold, quality score, number of unpopped kernels and number of kernels per 10 grams, but was non-significant for moisture content. Site by line by tester interaction effects were significant for quality score and number of kernels per 10 grams. Popping method by line interaction effects, method by tester effects, method by line by tester effects, site by method by line effects, site by method by tester effects and site by method by line by tester interaction effects was non-significant for all traits.

5.4.4 Gene action

Mean squares for GCA and SCA for popping quality traits are shown in Table 5.4. GCA due to lines was highly significant for all traits. GCA due to testers was significant for flake volume, popping fold, number of unpopped kernels and number of kernels per 10 grams.

GCA due to testers was non-significant for moisture content and quality score. SCA was significant for flake volume, popping fold and number of kernels per 10 grams. SCA was non-significant for number of unpopped kernels, moisture content and quality score. Proportions for GCA and SCA, as shown in Table 5.5, indicate that GCA (85.99%) was more important than SCA (14.01%) in the conditioning of flake volume and popping fold. A similar trend, where GCA was greater than SCA, was observed for the number of unpopped kernels (GCA = 93.07%; SCA = 6.93%), quality score (GCA = 90.69%; SCA = 9.31%), moisture content (GCA = 85.21%; SCA = 14.79%) and number of kernels per 10 grams (GCA = 93.55%; SCA = 6.45%). A significant and large proportion of total GCA was observed for all traits. Heritability estimates for popping quality traits are shown in Table 5.4. These are flake volume (76%), popping fold (74%), number of kernels per 10 grams (71%), moisture content (-3%) and number of unpopped kernels (71%).

Table 5. 4: Line by tester analysis of hybrids for popping ability

		Flake Volume		**Popping Fold**		**Unpopped Kernels**		**Grain moisture content**		**Quality Score**		**Number of kernels per 10g**	
Source	DF	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F	MS	Pr > F
Site	1	643430.80	<.0001	257.29	<.0001	51882.74	<.0001	19.74	0.0996	30.12	<.0001	4705.97	<.0001
Rep	1	26087.30	0.2928	10.45	0.2925	66832.58	<.0001	10.15	0.2371	0.01	0.8566	22.23	0.4754
Method	1	1222372.21	<.0001	489.07	<.0001	160663.69	<.0001	8.46	0.223	0.60	0.001	214.34	<.0001
Female	47	81720.31	<.0001	32.69	<.0001	1317.77	0.0009	11.39	0.0174	0.59	0.0015	259.25	<.0001
Male	44	70226.15	<.0001	28.09	<.0001	3113.20	<.0001	7.80	0.3717	0.28	0.6071	79.94	0.0179
Female*Male	20	56470.19	0.0007	22.59	0.0007	685.60	0.513	9.04	0.1451	0.44	0.0552	67.70	0.0187
Site*Female	46	35224.81	0.0222	14.09	0.0221	744.55	0.4046	11.37	0.0186	0.45	0.051	70.79	0.0126
Site*Male	43	22241.38	0.5725	8.90	0.5723	829.28	0.2331	8.38	0.291	0.31	0.4654	78.29	0.0215
Site*Female*Male	20	11461.86	0.9711	4.58	0.9711	655.27	0.5673						
Method*Female	47	20554.37	0.7092	8.22	0.7086	788.42	0.3045						
Method*Male	44	22380.68	0.5631	8.95	0.5629	687.76	0.546						
Method*Female*Male	20	11626.18	0.9687	4.65	0.9687	552.05	0.749						
Site*method*female	46	18089.76	0.8637	7.24	0.8632	513.68	0.9175						
Site*method*male	43	26241.07	0.2893	10.50	0.2891	638.03	0.6694						
Site*method*female*male	20	22259.46	0.5276	8.90	0.5275	433.99	0.9089						
Error		23518.29		9.41		715.69							
Heritability estimate		0.76		0.74		0.71		-0.03		0.61		0.91	
R^2		0.70		0.70		0.70		0.50		0.70		0.8	
CV (%)		14.7		14.7		52.8		0.7		27.9		9.6	
Mean		1046.0		20.9		50.6		12.9		2.0		69.0	

Table 5. 5: Proportion (%) of GCA and SCA for popping quality traits, estimated based on sum of squares.

	GCA			SCA
	Line GCA	**Tester GCA**	**Total GCA**	
Variable				
Flake Volume	47.65	38.34	85.99	14.01
Popping Fold	47.65	38.34	85.99	14.01
Unpopped Kernels	29.13	64.42	93.55	6.45
Moisture Content	37.71	47.51	85.21	14.79
Quality Score	47.16	43.53	90.69	9.31
Kernels per 10g	43.65	49.42	93.07	6.93

5.4.5 Relationships among popping quality traits

Relationships among popping quality traits are presented in Table 5.6. Results indicate a significant (P≤0.01) strong correlation (r= 1.00) for flake volume with popping fold. There was a significant (P≤0.01) weak and negative correlation (r= -0.31) between flake volume and popping fold with number of unpopped kernels and kernel size (r= -0.27). There was significant (P≤0.01) and strong positive correlation (r= 0.56) between kernel size and number of unpopped kernels. Moisture content showed a significant (P≤0.05) weak and positive correlation with kernel size (r= 0.09) and number of unpopped kernels (r= 0.11). Correlation was not significant for flake volume and popping fold with moisture content.

Table 5. 6: Phenotypic correlations among popping quality traits

Variable	Moisture Content	Flake Volume	Popping Fold	Unpopped Kernels
Moisture Content				
Flake Volume	-0.05			
Popping Fold	-0.05	1.00**		
Unpopped Kernels	0.11*	-0.31**	-0.31**	
Kernels per 10g	0.09*	-0.27**	-0.27**	0.56**

**,* = r value significant at P≤0.01 and P≤0.05, respectively.

5.5 Discussion

5.5.1 Variability among hybrids for quality traits

There were significant differences among hybrids for all traits except moisture content. Variability of hybrids that was observed in this study presents an opportunity to select for superior hybrids for popping ability. Significant variability among popcorn hybrids for quality traits were reported in previous studies (Daros *et al.*, 2004; Sakın *et al.*, 2005; Moterle *et al.*, 2012). The non-significant variation of hybrids for moisture content indicates that there were non-significant differences in moisture content for the samples of popcorn grain that were popped. Therefore the moisture differences could not be used to explain the variation observed among hybrids for flake volume. The check hybrid was ranked 16th in terms of popping ability. There were therefore fifteen experimental hybrids identified, which performed better than the check hybrid grown and popped under the same conditions. Quality in popcorn is important. In addition to high popping expansion volume, popcorn flakes that are tender, uniformly coloured, free from tough hulls and are free from objectionable flavours are desirable to consumers (Ziegler, 1984). In the present study, quality scores used ranged from 1 to 5, with the score of 1 being the best quality and the score of 5 being the worst quality. Hybrids that were evaluated in the study had quality scores which varied between 1.2 and 3.1. The check, hybrid P618, had a quality score of 1.6. Hybrids which performed well in terms of quality were identified. Six hybrids out of the top 15 had a quality score of 1.6 and below.

5.5.2 Gene action

Additive gene action was found to be more prominent in the conditioning of all quality traits. Proportions for GCA and SCA showed that GCA was more important than SCA in the conditioning of flake volume and popping fold. A similar trend, where GCA was greater than SCA, was observed for number of unpopped kernels, quality score, moisture content and number of kernels per 10 grams. Since GCA is an indicator for additive gene action, results show that additive gene action is more important for conditioning of popping quality traits. This suggests a good opportunity to select for popping quality traits. Previous studies have reported additive gene action for popping expansion volume (Pajic´ and Babic´, 1991; Pereira and Amaral Júnior do, 2001; Miranda *et al.*, 2008; Pajic´, 2008) and popping fold (Li, 2007). Successes in selection of popcorn varieties are reported in the literature (Daros *et al.*, 2004; Viana, 2009; Amaral Júnior do *et al.*, 2010; Arnhold *et al.*, 2010). All traits except moisture content were found to have high heritability scores. This indicates that inheritance of quality traits is due to additive gene action. Similar results were reported in previous studies.

Heritability values of all traits were high, indicating the opportunity for effective selection to improve the hybrids. Moisture content was the only trait with a negative value, indicating that there was not any significant variation among hybrids for this trait. High heritability values for these traits were reported in previous studies (Lu *et al.*, 2003; Babu *et al.*, 2006; Li *et al.*, 2007b)

5.5.3 Relationships among popping quality traits

The results indicate a significant strong correlation for flake volume with popping fold. The study showed that hybrids with high flake volumes were the ones with high popping fold. These traits are therefore directly correlated. Positive correlation between these traits was also reported by Li *et al.* (2007). There was a significant weak and negative correlation between flake volume and popping fold with number of unpopped kernels, as well as kernel size. The greater the number of unpopped kernels left after popping, the smaller the flake volume. According to Singh *et al.* (1997), unpopped kernels are not desirable because they do not contribute to expansion volume and are considered to be defective. A negative relationship was observed between flake volume and popping fold with the number of kernels per 10 grams. This means that small kernels do not pop well and hence fail to contribute effectively to flake volume and popping fold. Large and medium sized kernels are therefore preferred, to achieve high expansion volumes. There was significant and strong positive correlation between the number of kernels per 10 grams and the number of unpopped kernels. The relationship indicates that the smaller the kernel size, the larger the number of unpopped kernels. Moisture content showed a significant weak and positive correlation with the number of kernels per 10 grams and number of unpopped kernels. These results show that the moisture content for large kernels was lower than that for small kernels. The positive relationship between moisture content and number of unpopped kernels suggests that, as the moisture content increases, the number of unpopped kernels increases. Correlation was not significant for flake volume and popping fold with moisture content.

5.5.4 Genotype x environment interaction effects on popping quality traits

The results indicate that site effects were highly significant for all traits, namely flake volume, popping fold, number of unpopped kernels, moisture content, quality score and number of kernels per 10 grams. Popping quality traits were therefore affected by different sites. The effect of popping method was significant for flake volume, popping fold and number of unpopped kernels. The results concur with previous studies (Broccoli and Burak, 2004). However, the genotype x popping method interaction was not significant, indicating that the hybrids were stable.

There was no significant genotype x site interaction effects for quantitative traits, indicating that the hybrids were stable for popping ability. Nevertheless, significant genotype x site interaction was observed for the quality score and kernel size, indicating that quality performance depends on where the popcorns were produced. Site by line by tester interaction effects were significant for quality score and number of kernels per 10 grams. The lines and testers interacted with the environment for these traits. Method by line interaction effects, method by tester effects, method by line by tester effects, site by method by line effects, site by method by tester effects and site by method by line by tester interaction effects were non-significant for all traits. This suggests that genotype by site interaction effects were generally minimal for popping quality traits.

5.6 Conclusion

The significant variability that was observed in the study among hybrids for popping quality traits presents an opportunity for selection of hybrids with good popping ability. The top 15 hybrids would be recommended for further testing.

Additive gene action was more prominent than non-additive action for all popping quality traits. Popping quality traits were found to be highly heritable. This creates an opportunity to effectively improve these traits through selection. There was a significant weak and negative correlation between flake volume and popping fold, flake volume and number of unpopped kernels, as well as between flake volume and number of kernels per 10 grams.

Although both site and popping method main effects were significant for popping ability, results do not support a significant role of GxE. Site effects were highly significant for all traits. The effect of popping method was significant for flake volume, popping fold and number of unpopped kernels. Entry x site x popping method, entry x site and entry x popping method interaction were not significant for all quantitative traits.

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General discussion, conclusion and recommendations

6.1 Introduction

The purpose of this chapter is to discuss the major findings of the study, the implications of the findings and recommendations for future research. The following hypotheses were tested in the study:

a) Economically important traits in popcorn are influenced by additive gene action.
b) There are significant positive relationships between agronomic and popping quality traits that can be exploited in breeding new popcorn hybrids.
c) There are significant differences between inbred lines for popping ability.
d) There are significant differences among hybrids for popping ability and yield.

6.2 Study findings and their implications

6.2.1 Findings from the literature

Popcorn is a high value crop, with possible multiplier effects such as income generation for under-resourced communities. In Brazil, the economic value of popcorn is reported to be three times that of dent maize (Moterle *et al.*, 2012). In South Africa, the price of popcorn has been observed to be more than three times that of dent maize. Genetic variation in popcorn is important, because variety improvement depends on it.

Despite the popularity of popcorn as a snack in Africa, commercial production does not meet the demand. Popcorn grain is largely imported from developed countries like the USA. This is due to lack of adapted varieties with good popping ability and superior agronomic traits. Although popcorn production in developing countries is hindered by poor agronomic traits which affect quality, it can be improved through relevant breeding programmes. Breeding programmes targeted at improving popcorn varieties are progressing at a very slow pace compared to those directed at improving dent maize varieties. In South Africa, breeding efforts for popcorn were last reported in 1954 (Josephson *et al.*, 1954). In Africa, recent breeding efforts have been reported only for Nigeria and they are still incipient (Iken and Amusa, 2010). Popcorn consumption and production trends are scarcely reported for African countries.

In popcorn, both yield and popping quality are important (Sakın *et al.*, 2005). In the current study, tests were conducted for both value for cultivation and use. The study identified inbred lines with good popping ability and hybrids which combine good yield and good popping ability. The literature indicates that popcorn is rich in nutrients, indicating that it can be transformed from just a snack to a food security crop.

6.2.2 Findings from the investigations conducted

6.2.2.1 Genotypic variation

Variability among inbred lines was statistically significant for number of kernels per 10g, flake volume, number of unpopped kernels and popping fold. Variability among inbred lines for grain moisture content was non-significant. Flake volume varied from 63 cm^3 to 850 cm^3, while popping fold varied from 2.5 to 34 times the original volume. This variation provides opportunities for selection, in line with the need for new popcorn breeding programmes. The line DPL 116 gave the highest flake volume of 850 cm^3 and the lines thus have some utility for breeding hybrids. The check hybrid P618 ranked 23rd in terms of flake volume and popping fold. The majority of inbred lines had small kernels, with the kernel count of 76 to 105 kernels per 10 g. This could be due to inbreeding depression associated with inbred lines after many generations of self-pollination.

The study involving hybrids showed that hybrids were significantly different for grain yield and yield components across sites. Means for grain yield ranged from 1.0 t/ha to 5.2 t/ha. The results showing significant variation of hybrids for agronomic traits are in line with previous studies. The commercial hybrid P618 was ranked 42nd for yield. The yields obtained in the study are above those obtained in the study conducted in Brazil between 2003 and 2005, which indicated mean yields between 1.0 and 1.7 t/ha for hybrids. New genotypes which outperformed the standard check hybrid, exceeding the mean yield of 2.9 t/ha were identified, including POPH13, POPH24, POPH37, POPH19, POPH110 and POPH17. These hybrids had good popping quality and yield. This characterizes a good popcorn. Certain hybrids failed to meet this requirement because they did not exhibit reasonable yield in spite of their excellent popping ability. Examples of such hybrids listed in the top 15 for popping are POPH82, POPH33, POPH43, POPH117 and POPH22 (Table 6.1).

The study revealed significant GCA and SCA effects for grain yield, ear length, number of ears per plant and plant height. This indicates the importance of both additive and non-additive gene action in the conditioning of these traits. However, in general, the additive effects were more important because the proportion of GCA was greater than that of GCA in all traits. The greater GCA sum of squares for GCA for grain yield, ear length, plant height and ear position indicate that additive gene action is more important than non-additive gene action for the conditioning of these traits. Generally the results confirm previous findings from the literature.

The general observations made in the study concerning popping quality traits in hybrids indicate that the highest flake volumes were obtained from large kernels with kernel counts of 52-67 kernels per 10 grams. The top 15 hybrids for popping performance were in this category. It was found that 52% of the hybrids evaluated by the study had large kernels. It was reported previously that the highest popping volumes result from the medium- sized kernels (Song *et al.*, 1991). This supports the need to select for large and medium sized kernels in addition to selecting for higher yields.

In terms of popping quality traits, there was significant variation among hybrids for all traits except grain moisture content. This indicates a good opportunity for selecting for popping quality traits. An important finding was that popcorn hybrids which displayed the highest yield were among the lowest in terms of popping. This implied a negative association between the two traits. This impact negatively on breeding progress, because as the breeder makes progress in improving one trait, another trait is compromised. This can partly explain why there has been slow progress in popcorn breeding when compared to dent maize.

6.2.2.2 Nature of gene action for quality traits

Additive gene action was found to be more prominent in the conditioning of all quality traits. Proportions for GCA and SCA showed that GCA was more important than SCA in the conditioning of flake volume and popping fold. A similar trend, where GCA is greater than SCA, was observed for the number of unpopped kernels, quality score and number of kernels per 10 g. Since GCA is an indicator for additive gene action, the results show that additive gene action is more important for conditioning of popping quality traits. This suggests a good opportunity for selecting for popping quality traits. Whereas previous studies have reported additive gene action for popping expansion volume (Pajic´ and Babic´, 1991; Pereira and Amaral Júnior do, 2001; Miranda *et al.*, 2008; Pajic´, 2008) and popping fold (Li, 2007), there is no reference in the literature to gene action for number of unpopped kernels, number of kernels per 10 g and quality score. Therefore the results of the current study form the baseline for these traits.

Table 6. 1: Means for hybrid performance in terms of agronomic and quality traits

Entry	Name	Relative to control P618 (%)		Mean		Rank		Popping fold	UPK	KN10g	MC	QS	NCLB
		Flake volume	Yield	Flake volume (cm^3)	Yield (t/ha)	Flake Volume	Yield						
13	11POPH13	111.35	108.19	1287.5	3.1	1	30	25.8	29.1	65.8	13.1	2.2	2.6
81	11POPH81	108.10	109.48	1250.0	3.2	2	27	25.0	47.4	67.1	12.7	1.7	3.1
82	11POPH82	106.48	80.78	1231.3	**2.3**	3	84	24.6	32.5	65.3	12.9	1.6	3.3
24	11POPH24	105.40	113.79	1218.8	3.3	4	21	24.4	34.1	55.8	13.1	1.3	2.9
37	11POPH37	105.40	97.93	1218.8	2.8	6	50	24.4	47.4	65.3	12.9	2.2	3.3
33	11POPH33	105.40	84.57	1218.8	**2.5**	5	75	24.4	46.8	64.0	12.6	1.6	3.0
21	11POPH21	104.86	101.90	1212.5	3.0	7	38	24.3	44.8	65.8	12.8	1.5	3.1
19	11POPH19	103.91	101.64	1201.6	2.9	8	39	24.0	35.9	65.4	12.8	1.5	3.0
110	11POPH110	102.70	103.88	1187.5	3.0	9	36	23.8	20.9	60.6	12.9	1.8	3.3
43	11POPH43	102.43	86.47	1184.4	2.5	10	70	23.7	45.5	65.0	13.2	2.2	2.8
14	11POPH14	101.62	96.21	1175.0	2.8	11	56	23.5	51.9	68.6	13.0	1.2	2.8
17	11POPH17	101.35	109.91	1171.9	3.2	12	26	23.4	52.4	66.4	13.0	2.0	3.0
117	11POPH117	101.35	50.43	1171.9	1.5	13	119	23.4	38.7	63.4	12.9	2.0	3.1
22	11POPH22	101.08	94.31	1168.8	2.7	14	61	23.4	55.3	65.4	13.0	1.8	3.1
116	11POPH116	101.08	68.71	1168.8	2.0	15	101	23.4	64.0	72.4	12.9	1.9	3.1
120	**P618**	**100.00**	**101.03**	**1156.3**	**2.9**	**16**	**42**	**23.1**	**53.9**	**64.0**	**13.0**	**1.6**	**3.3**
23	11POPH23	70.54	112.93	815.6	3.3	116	23	16.3	24.8	52.1	12.7	1.7	3.0
87	11POPH87	70.00	78.36	809.4	2.3	117	88	16.2	44.9	68.5	12.6	2.7	3.3
20	11POPH20	65.40	180.86	756.3	5.2	118	1	15.1	29.8	50.0	12.8	2.2	2.4
108	11POPH108	64.86	137.07	750.0	4.0	119	4	15.0	29.3	69.0	12.7	2.3	2.4
68	11POPH68	63.51	122.50	734.4	3.6	120	12	14.7	18.8	49.1	12.9	2.3	2.6

NCLB = Northern Corn Leaf Blight; KN10g = Number of kernels per 10 g of popcorn grain; MC = Moisture content; UPK = Number of unpopped kernels; QS = Quality score

6.2.2.3 Genotype x environment interaction

Entry by site interaction effects were highly significant for stem lodging and days to mid-pollination, supporting the observation of genotype x environment interaction effects for these traits. This implies that standing ability and flowering dates for the hybrids is dependent on the environment. It was also found that the NCLB disease was positively correlated with stem lodging indicating that disease infection weakened the plant stalks, which aggravated stem lodging, especially at Cedara, where the disease severity was higher than at Ukulinga farm.

There were non-significant entry x site interaction effects for NCLB, ear length, plant height, ear position, shelling percentage, number of ears per plant and grain yield. This means that the hybrids were generally stable for most of the traits. Effectively, entry x site interaction played a minimal role in conditioning these traits which enhanced heritability. However, these findings are in contrast with the results of previous studies (Broccoli and Burak, 2004; Scapim *et al.*, 2010).

The effect of popping method was significant for flake volume, popping fold and number of unpopped kernels. These results were in agreement with previous studies (Broccoli and Burak, 2004). There were non-significant site x entry, entry x popping method, and site x entry x popping method interactions for flake volume, number of unpopped kernels, popping fold. This suggests that popping ability does not depend on the method used and the sites where the crop was grown. This suggests that genotype by environment interaction effects were generally minimal for popping ability. Nonetheless, popping quality traits were in general affected by GxE effects; because the site x entry interaction effects was significant for quality score and kernel size. Consistent with this observation, the site by line by tester interaction effects were significant for quality score and number of kernels per 10 grams. The significance of GxE for these traits can possibly complicate selection for these traits, due to instability of performance.

6.2.2.4 Association between agronomic and popping traits

Grain yield showed significant positive correlation with ear length, plant height, ear position, shelling percentage and number of ears per plant (Table 6.2). This is an indication that these secondary traits of yield influence grain yield positively. The findings of this study, in terms of these relationships are in line with previous studies. Grain yield showed significant negative correlation with NCLB and stem lodging. This indicates that, as NCLB disease and stem lodging increase, grain yield is affected negatively. NCLB was found to be positively correlated to stem lodging. Plants that are severely infected by NCLB tend to be prone to stem lodging.

The findings of the study in terms of popping quality traits indicate a significant strong correlation for flake volume with popping fold, showing the most expansion from the original kernel volume. The study showed that hybrids with high flake volumes are the ones with high popping fold. These traits are directly correlated. Positive correlation between these traits was also reported by Li *et al.* (2007). There was a significant weak and negative correlation between flake volume and number of unpopped kernels as well as kernel size. The greater the number of unpopped kernels left after popping, the smaller the flake volume. Unpopped kernels are not desirable because they do not contribute to expansion volume and are considered to be defective (Singh *et al.*, 1997). A negative relationship was observed between flake volume and number of kernels per 10 g. This means that small kernels do not pop well and hence fail to contribute effectively to flake volume and popping fold. Large and medium sized kernels are therefore preferred, to achieve high expansion volumes. There was significant and strong positive correlation between number of kernels per 10 g and number of unpopped kernels. The relationship further indicates that the smaller the kernel size, the larger the number of unpopped kernels.

Relationships between agronomic traits and popping quality traits showed that there is significant, but weak and positive correlation between NCLB and number of kernels per 10 g, suggesting that NCLB has a negative influence on kernel size (Table 6.2). Significant weak and negative correlation was observed between flake volume and stem lodging and also between popping fold and stem lodging. This suggests that weak stalks, which are prone to stem lodging, are not desired, as they impact on flake volume, which is a major determinant of popcorn quality. The number of kernels per 10 g was significantly and positively correlated to shelling percentage and stem lodging. The number of kernels per 10 g, was however, significantly and negatively correlated to plant height and grain yield, indicating that poor yield is associated with small kernels NCLB was significantly and positively correlated to quality score and number of unpopped kernels, indicating that NCLB infection leads to poor quality kernels which fail to pop effectively. Plant height was significantly negatively correlated to quality score and number of unpopped kernels. Stem lodging was significantly positively correlated to number of unpopped kernels, suggesting that poor standing ability prevents proper maturity of kernels, thus impacting negatively on kernel size. Quality score was significantly positively correlated to stem lodging and significantly negatively correlated to grain yield, which suggests that poor standing ability ultimately has a negative effect on the popcorn end product, resulting in poor quality flakes. The number of unpopped kernels was significantly negatively correlated to grain yield, suggesting that unpopped kernels which are small in size are associated with poor yield.

Table 6. 2: Phenotypic correlations among agronomic and popping quality traits

Variable	FV	PF	KN10g	MC	NCLB	PH	QS	SHELL	SL	UPK
PF	1**	-								
KN10g	-0.115	-0.115	-							
MC	0.029	0.029	0.066	-						
NCLB	0.056	0.056	0.33**	0.068	-					
PH	0.099	0.0985	-0.40**	0.033	-0.21*	-				
QS	-0.49**	-0.49**	0.34**	-0.027	0.23*	-0.26*	-			
SHELL	0.004	0.004	0.25*	0.022	0.22	-0.19*	0.087	-		
SL	-0.24*	-0.24*	0.39**	0.081	0.193	-0.19*	0.24*	0.139	-	
UPK	-0.155	-0.155	0.79**	0.071	0.28**	-0.41**	0.37**	0.145	0.35**	-
GY	-0.033	-0.033	-0.53**	0.054	-0.41**	0.54**	-0.27*	0.063	-0.24*	-0.52**

**,* = r value significant at P≤0.01 and P≤0.05, respectively. NCLB = Northern Corn Leaf Blight; EARL = ear length; PH = plant height; DMP = days to mid-pollination; EPO = ear position; SHELL = shelling percentage; EPP = number of ears per plant; SL = stem lodging; GY = grain yield. KN10g = Number of kernels per 10 grams of popcorn grain; MC = Moisture content; FV = flake volume; UPK = Number of unpopped kernels; PF = Popping fold (volume by volume basis); QS = Quality score

6.3 Conclusion and recommendations

The literature study revealed that there is a general lack of breeding programmes in Africa that are targeted at developing adapted popcorn varieties, despite increasing consumption and popularity. The current study is a positive step in identifying hybrids with value for cultivation and use.

Significant variation among inbred lines, as well as hybrids, which was observed in the study, is a positive indicator for fruitful breeding programmes towards developing adapted popcorn hybrids.

Additive gene action was generally dominant for both agronomic and popping quality traits, suggesting better chances for selection of new hybrids with good agronomic traits and popping ability. This is possible, because additive variance can be fixed through plant breeding. Most traits showed moderate to high heritability, which further increases opportunities for selection.

Significant positive relationships between agronomic and popping quality traits were observed, particularly between grain yield and kernel size. Most hybrids developed by the current study were large and associated with high popping ability. Selection should be for large kernels, which are linked to high yield and greater popping ability and quality.

The study was able to identify hybrids with reasonable yield and good popping ability. These hybrids require further testing, provided they meet the popping ability threshold. Suitable hybrids identified include POPH 13, POPH 81, POPH 24 and POPH 14. POPH 14 demonstrated superiority in yield, flake volume and had the best quality score. Some hybrids identified showed acceptable resistance to NCLB disease, indicating that they can be used by small-holder farmers, who have limited access to fungicides. The literature study indicated that popcorn is rich in nutrients. This can be exploited for the benefit of rural communities and can be included in future studies.

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APPENDICES

Appendix 1: Means for popping quality traits for 128 popcorn inbred lines

Rank	Entry Name	Kernels per 10g	Moisture Content	Flake Volume	Unpopped Kernels	Popping Fold
1	DPL16	90	13.6	500	119	20.0
2	DPL115	73	13.5	235	120	9.4
3	DPL49	120	13.5	200	210	8.0
4	DPL116	85	13.5	850	9	34.0
5	DPL30	77	13.5	238	61	9.5
6	DPL77	108	13.5	200	133	8.0
7	DPL110	86	13.4	375	101	15.0
8	DPL9	110	13.4	338	127	13.5
9	DPL66	127	13.4	300	191	12.0
10	DPL114	119	13.4	158	202	6.3
11	DPL102	78	13.4	153	134	6.1
12	DPL135	79	13.4	430	104	17.2
13	DPL12	102	13.4	363	122	14.5
14	DPL105	75	13.4	323	92	12.9
15	DPL103	84	13.4	288	149	11.5
16	DPL136	77	13.4	275	94	11.0
17	DPL67	103	13.4	188	191	7.5
18	DPL93	103	13.4	163	151	6.5
19	DPL112	113	13.4	90	144	3.6
20	DPL7	83	13.3	588	94	23.5
21	DPL31	87	13.3	513	56	20.5
22	DPL27	119	13.3	400	109	16.0
23	DPL40	72	13.3	350	66	14.0
24	DPL106	98	13.3	343	138	13.7
25	DPL13	124	13.3	263	168	10.5
26	DPL29	112	13.3	242	149	9.7
27	DPL28	88	13.3	238	117	9.5
28	DPL76	111	13.3	238	118	9.5
29	DPL14	122	13.3	138	202	5.5
30	DPL117	94	13.3	655	40	26.2
31	DPL50	102	13.3	300	131	12.0
32	DPL97	101	13.3	245	142	9.8
33	DPL45	93	13.3	225	166	9.0
34	DPL130	97	13.2	425	106	17.0
35	DPL23	77	13.2	300	104	12.0
36	DPL70	130	13.2	300	168	12.0
37	DPL11	108	13.2	288	146	11.5

Rank	Entry Name	Kernels per 10g	Moisture Content	Flake Volume	Unpopped Kernels	Popping Fold
38	DPL52	85	13.2	265	150	10.6
39	DPL43	73	13.2	138	134	5.5
40	DPL34	56	13.2	125	61	5.0
41	DPL33	51	13.2	113	44	4.5
42	DPL51	102	13.2	113	225	4.5
43	DPL47	75	13.2	500	49	20.0
44	DPL129	88	13.2	500	79	20.0
45	DPL95	86	13.2	325	91	13.0
46	DPL21	91	13.2	243	102	9.7
47	DPL44	86	13.2	213	136	8.5
48	DPL73	90	13.2	200	157	8.0
49	DPL122	92	13.2	200	144	8.0
50	DPL91	91	13.2	185	125	7.4
51	DPL120	91	13.2	163	128	6.5
52	DPL107	87	13.2	115	150	4.6
53	DPL8	98	13.1	415	109	16.6
54	P618-F1	73	13.1	413	97	16.5
55	DPL65	103	13.1	313	124	12.5
56	DPL119	110	13.1	300	126	12.0
57	DPL61	99	13.1	263	157	10.5
58	DPL111	97	13.1	230	140	9.2
59	DPL113	98	13.1	213	146	8.5
60	DPL124	90	13.1	200	146	8.0
61	DPL15	101	13.1	188	156	7.5
62	DPL75	98	13.1	175	178	7.0
63	DPL38	59	13.1	113	47	4.5
64	DPL94	81	13.1	488	30	19.5
65	DPL118	73	13.1	313	76	12.5
66	DPL74	114	13.1	238	147	9.5
67	DPL48	143	13.1	200	235	8.0
68	DPL104	105	13.1	175	145	7.0
69	DPL98	93	13.1	138	139	5.5
70	DPL35	71	13.1	75	106	3.0
71	DPL36	57	13.1	75	77	3.0
72	DPL131	89	13.0	513	91	20.5
73	DPL53	105	13.0	438	99	17.5
74	DPL90	90	13.0	425	106	17.0
75	DPL10	119	13.0	363	118	14.5
76	DPL109	105	13.0	350	111	14.0
77	DPL63	107	13.0	288	140	11.5
78	DPL6	89	13.0	250	126	10.0
79	DPL133	95	13.0	230	153	9.2
80	DPL55	118	13.0	225	91	9.0
81	DPL101	72	13.0	220	91	8.8

Rank	Entry Name	Kernels per 10g	Moisture Content	Flake Volume	Unpopped Kernels	Popping Fold
82	DPL132	85	13.0	213	132	8.5
83	DPL88	157	13.0	138	215	5.5
84	DPL108	90	13.0	128	148	5.1
85	DPL89	120	13.0	565	63	22.6
86	DPL57	107	13.0	375	115	15.0
87	DPL134	100	13.0	315	123	12.6
88	DPL39	87	13.0	250	103	10.0
89	DPL37	46	13.0	175	26	7.0
90	DPL96	84	13.0	175	133	7.0
91	DPL92	98	13.0	163	96	6.5
92	DPL128	77	13.0	125	148	5.0
93	DPL56	127	12.9	650	32	26.0
94	DPL2	84	12.9	463	65	18.5
95	DPL127	89	12.9	450	95	18.0
96	DPL84	79	12.9	375	77	15.0
97	DPL5	91	12.9	313	125	12.5
98	DPL19	83	12.9	275	43	11.0
99	DPL58	118	12.9	200	158	8.0
100	DPL60	97	12.9	175	150	7.0
101	DPL62	95	12.9	175	149	7.0
102	DPL121	92	12.9	160	146	6.4
103	DPL46	99	12.9	263	96	10.5
104	DPL126	87	12.9	145	149	5.8
105	DPL54	120	12.8	500	84	20.0
106	DPL99	94	12.8	475	55	19.0
107	DPL26	83	12.8	375	93	15.0
108	DPL100	78	12.8	375	69	15.0
109	DPL59	102	12.8	350	118	14.0
110	DPL64	95	12.8	188	165	7.5
111	DPL3	101	12.8	500	49	20.0
112	DPL1	74	12.8	438	46	17.5
113	DPL123	62	12.8	170	77	6.8
114	DPL79	84	12.8	125	150	5.0
115	DPL20	104	12.7	313	85	12.5
116	DPL85	79	12.7	225	143	9.0
117	DPL4	101	12.7	188	142	7.5
118	DPL125	90	12.6	213	148	8.5
119	DPL71	135	12.4	125	201	5.0
120	DPL78	113	12.0	276	144	11.0
121	DPL41	116	11.6	125	145	5.0
122	DPL81	80	11.3	138	121	5.5
123	DPL86	80	11.0	175	120	7.0
124	DPL87	93	11.0	113	149	4.5
125	DPL80	81	10.8	63	128	2.5

Rank	Entry Name	Kernels per 10g	Moisture Content	Flake Volume	Unpopped Kernels	Popping Fold
126	DPL82	72	10.8	250	43	10.0
127	DPL72	128	10.6	113	222	4.5
128	DPL68	126	10.3	375	103	15.0

Appendix 2: Means for agronomic traits of 120 popcorn hybrids across 2 sites

Entry	**Name**	**Grain yield**			**NCLB**	**EARL**	**PH**	**DMP**	**EPO**	**SHELL**	**EPP**	**SL**
		Relative to control P618	**Mean (t/ha)**	**Rank**								
1	11POPH1	79.48	2.3	86	3.1	19.0	208.0	72.3	0.43	0.75	0.9	27.5
2	11POPH2	86.03	2.5	71	3.6	20.6	201.5	74.3	0.51	0.77	1.3	20.4
3	11POPH3	74.74	2.2	94	3.5	20.7	223.3	72.3	0.49	0.74	1.2	32.5
4	11POPH4	66.38	1.9	104	3.5	20.4	229.8	72.0	0.46	0.72	1.2	32.3
5	11POPH5	93.10	2.7	64	3.3	20.2	227.5	72.0	0.46	0.73	1.5	12.7
6	11POPH6	98.53	2.9	47	3.1	18.9	226.3	72.8	0.48	0.73	1.5	23.8
7	11POPH7	114.91	3.3	19	3.0	19.3	228.8	70.8	0.48	0.75	1.4	19.5
8	11POPH8	66.03	1.9	105	3.6	18.7	216.8	71.3	0.46	0.97	1.0	33.1
9	11POPH9	125.60	3.6	9	3.0	18.9	239.8	71.8	0.59	0.76	1.8	52.7
10	11POPH10	101.29	2.9	41	3.3	19.5	233.8	73.3	0.48	0.74	1.1	26.7
11	11POPH11	96.29	2.8	55	2.8	20.5	224.0	72.3	0.45	0.70	1.1	12.5
12	11POPH12	50.60	1.5	118	2.8	19.2	219.3	72.3	0.46	0.74	1.3	20.8
13	11POPH13	108.19	3.1	30	2.6	18.7	222.0	71.8	0.49	0.73	1.4	15.5
14	11POPH14	96.21	2.8	56	2.8	20.1	251.8	73.0	0.54	0.72	1.5	13.6
15	11POPH15	84.57	2.5	74	3.0	20.5	211.0	71.5	0.50	0.75	1.3	38.3
16	11POPH16	52.67	1.5	117	3.4	16.3	195.8	71.8	0.45	0.73	1.1	54.2
17	11POPH17	109.91	3.2	26	3.0	17.9	220.0	70.8	0.47	0.75	1.3	40.6
18	11POPH18	98.10	2.8	49	2.8	19.1	210.5	71.5	0.47	0.73	1.0	0.0
19	11POPH19	101.64	2.9	39	3.0	20.8	244.5	72.8	0.54	0.73	1.4	24.3
20	11POPH20	180.86	5.2	1	2.4	24.4	270.8	76.0	0.61	0.74	1.6	1.7
21	11POPH21	101.90	3.0	38	3.1	19.6	229.3	69.8	0.44	0.76	1.4	7.7
22	11POPH22	94.31	2.7	61	3.1	20.0	242.5	71.8	0.48	0.71	1.5	13.3
23	11POPH23	112.93	3.3	23	3.0	23.0	256.3	72.3	0.50	0.73	1.6	8.2
24	11POPH24	113.79	3.3	21	2.9	20.2	252.8	73.5	0.53	0.70	1.3	4.8

Entry	Name	Grain yield			NCLB	EARL	PH	DMP	EPO	SHELL	EPP	SL
		Relative to control P618	Mean (t/ha)	Rank								
25	11POPH25	96.38	2.8	54	3.5	21.9	253.0	69.8	0.53	0.78	1.0	33.3
26	11POPH26	113.88	3.3	20	2.9	19.6	251.8	72.3	0.58	0.77	1.5	16.8
27	11POPH27	75.78	2.2	92	3.3	19.0	245.8	71.5	0.44	0.80	1.2	15.1
28	11POPH28	78.45	2.3	87	3.0	18.4	206.5	71.5	0.49	0.75	1.0	8.3
29	11POPH29	82.67	2.4	82	2.9	17.4	228.8	72.0	0.51	0.74	1.4	38.2
30	11POPH30	135.00	3.9	5	3.0	21.6	227.0	70.0	0.51	0.72	1.5	28.9
31	11POPH31	59.74	1.7	110	3.4	20.7	223.5	71.3	0.45	0.53	0.8	14.3
32	11POPH32	53.53	1.6	116	3.3	18.4	217.8	71.5	0.41	0.70	1.2	32.0
33	11POPH33	84.57	2.5	75	3.0	19.2	243.8	70.0	0.46	0.70	1.1	12.0
34	11POPH34	72.33	2.1	96	3.6	16.6	226.0	72.5	0.49	0.76	1.4	34.8
35	11POPH35	62.50	1.8	107	3.3	19.0	210.8	72.3	0.42	0.71	1.1	25.1
36	11POPH36	89.48	2.6	67	2.8	16.9	239.8	73.5	0.54	0.75	1.3	48.8
37	11POPH37	97.93	2.8	50	3.3	20.6	225.0	71.8	0.49	0.73	1.4	43.1
38	11POPH38	70.34	2.0	99	3.6	17.3	220.0	71.8	0.51	0.76	1.5	25.0
39	11POPH39	82.84	2.4	79	3.6	18.9	216.3	73.0	0.49	0.92	1.0	27.7
40	11POPH40	64.31	1.9	106	3.4	18.2	220.5	72.8	0.51	0.71	1.7	40.4
41	11POPH41	100.60	2.9	43	3.3	16.5	236.0	72.0	0.56	0.75	1.9	16.5
42	11POPH42	93.53	2.7	62	3.3	17.1	209.3	71.0	0.47	1.02	1.3	28.9
43	11POPH43	86.47	2.5	70	2.8	19.4	205.3	71.0	0.47	0.77	1.1	22.4
44	11POPH44	98.53	2.9	48	2.9	17.1	231.0	71.0	0.54	0.77	1.5	13.3
45	11POPH45	82.41	2.4	83	3.1	20.0	236.3	70.3	0.47	0.75	1.3	16.5
46	11POPH46	77.84	2.3	89	3.5	20.5	226.8	71.8	0.50	0.79	1.1	30.8
47	11POPH47	106.81	3.1	32	3.1	17.7	233.8	71.5	0.54	0.74	1.6	5.0
48	11POPH48	96.81	2.8	53	3.5	19.2	209.5	72.3	0.48	0.88	1.5	30.5
49	11POPH49	108.53	3.1	29	3.0	18.8	234.0	72.3	0.53	0.72	1.8	36.9
50	11POPH50	71.12	2.1	97	3.0	17.8	225.3	71.0	0.48	0.71	1.2	38.8

Entry	Name	Grain yield			NCLB	EARL	PH	DMP	EPO	SHELL	EPP	SL
		Relative to control P618	Mean (t/ha)	Rank								
51	11POPH51	57.93	1.7	112	2.9	19.1	217.0	70.5	0.49	0.70	1.1	21.2
52	11POPH52	57.93	1.7	113	3.1	16.6	205.0	69.5	0.45	0.71	1.3	17.0
53	11POPH53	82.76	2.4	80	3.0	20.0	214.3	69.8	0.46	0.73	1.0	15.4
54	11POPH54	68.53	2.0	102	3.0	18.1	216.3	69.0	0.41	0.71	1.0	14.2
55	11POPH55	99.14	2.9	45	3.3	20.4	226.8	70.5	0.49	0.74	1.4	25.0
56	11POPH56	54.31	1.6	115	3.0	18.6	194.3	69.3	0.40	0.73	1.1	45.0
57	11POPH57	82.76	2.4	81	2.9	20.4	237.3	70.5	0.47	0.74	1.2	23.7
58	11POPH58	112.67	3.3	24	3.3	20.3	228.3	70.3	0.48	0.73	1.5	21.3
59	11POPH59	101.38	2.9	40	3.0	19.9	240.0	71.8	0.45	0.75	1.3	31.4
60	11POPH60	119.66	3.5	15	3.4	20.3	229.3	72.5	0.49	0.74	1.7	28.3
61	11POPH61	68.71	2.0	100	3.0	17.4	199.0	74.0	0.49	0.75	1.1	28.3
62	11POPH62	117.67	3.4	16	3.0	21.6	237.3	70.0	0.42	0.75	1.3	3.2
63	11POPH63	67.50	2.0	103	3.0	18.4	196.0	72.5	0.45	0.79	0.9	43.0
64	11POPH64	70.43	2.0	98	3.0	17.7	199.3	72.5	0.46	0.75	1.0	38.5
65	11POPH65	61.90	1.8	108	3.1	20.0	223.0	71.8	0.48	0.71	1.5	36.5
66	11POPH66	57.59	1.7	114	3.1	18.7	226.0	73.0	0.51	0.73	1.1	35.0
67	11POPH67	76.64	2.2	91	2.9	21.0	243.5	72.5	0.52	0.71	1.2	32.5
68	11POPH68	122.50	3.6	12	2.6	21.2	236.0	71.0	0.45	0.66	1.4	12.3
69	11POPH69	96.03	2.8	57	3.3	19.0	225.5	71.5	0.49	0.82	1.3	41.6
70	11POPH70	84.14	2.4	77	3.3	19.2	203.5	70.5	0.50	0.70	1.2	15.4
71	11POPH71	109.22	3.2	28	3.0	19.1	218.3	72.0	0.48	0.74	1.4	6.3
72	11POPH72	115.95	3.4	18	2.8	18.3	239.5	69.5	0.48	0.73	1.4	3.5
73	11POPH73	85.17	2.5	72	2.9	18.5	245.3	69.8	0.45	0.71	0.9	14.6
74	11POPH74	97.07	2.8	52	3.3	21.3	219.5	72.3	0.44	0.76	1.2	30.9
75	11POPH75	98.97	2.9	46	3.1	21.8	240.3	70.8	0.46	0.71	1.9	13.3
76	11POPH76	125.17	3.6	10	3.1	19.9	236.3	70.3	0.48	0.74	1.7	17.6

Entry	Name	Grain yield			NCLB	EARL	PH	DMP	EPO	SHELL	EPP	SL
		Relative to control P618	Mean (t/ha)	Rank								
77	11POPH77	99.31	2.9	44	2.9	17.7	235.8	71.3	0.50	0.80	1.6	26.3
78	11POPH78	97.59	2.8	51	3.3	17.2	234.3	71.3	0.47	0.76	1.8	29.2
79	11POPH79	103.88	3.0	35	3.0	18.1	221.8	70.8	0.49	0.76	1.3	12.5
80	11POPH80	85.09	2.5	73	3.3	19.3	221.3	72.5	0.52	0.75	1.4	24.4
81	11POPH81	109.48	3.2	27	3.1	19.1	233.3	74.5	0.53	0.75	1.5	11.0
82	11POPH82	80.78	2.3	84	3.3	21.3	241.8	71.0	0.48	0.72	1.3	25.0
83	11POPH83	129.66	3.8	8	3.1	21.3	236.5	72.8	0.51	0.73	1.4	16.7
84	11POPH84	59.74	1.7	111	3.3	16.7	222.5	74.5	0.50	0.72	1.5	64.1
85	11POPH85	95.17	2.8	58	3.4	17.4	229.8	72.5	0.53	0.75	1.4	38.9
86	11POPH86	61.21	1.8	109	3.6	18.2	227.3	74.0	0.54	0.74	1.3	49.1
87	11POPH87	78.36	2.3	88	3.3	17.4	216.5	72.5	0.52	0.76	1.3	30.8
88	11POPH88	105.17	3.1	34	3.1	18.3	226.8	71.0	0.51	0.74	1.5	4.7
89	11POPH89	93.53	2.7	63	2.9	18.1	211.8	72.0	0.50	0.78	1.5	34.9
90	11POPH90	110.34	3.2	25	2.8	17.9	235.3	71.5	0.52	0.78	1.4	21.9
91	11POPH91	77.76	2.3	90	3.5	17.2	240.8	72.5	0.53	0.75	1.4	38.5
92	11POPH92	121.81	3.5	13	2.9	18.0	248.8	71.3	0.57	0.75	1.8	47.1
93	11POPH93	108.02	3.1	31	3.1	18.7	262.0	71.5	0.53	0.74	1.9	20.4
94	11POPH94	87.07	2.5	69	3.3	18.6	242.0	74.5	0.53	0.71	1.5	6.6
95	11POPH95	91.98	2.7	65	3.4	20.0	239.5	74.0	0.50	0.70	1.5	14.2
96	11POPH96	146.55	4.3	2	3.0	17.6	239.5	72.8	0.55	0.77	1.7	17.7
97	11POPH97	87.76	2.5	68	2.8	18.1	223.8	73.3	0.50	0.71	1.1	20.8
98	11POPH98	113.28	3.3	22	3.0	21.0	254.5	71.5	0.60	0.74	1.4	38.6
99	11POPH99	132.24	3.8	6	2.9	20.6	229.0	70.8	0.53	0.73	1.6	34.8
100	11POPH100	33.97	1.0	120	3.0	17.4	191.8	76.0	0.51	0.70	1.2	39.6
101	11POPH101	83.62	2.4	78	3.5	20.6	254.3	72.8	0.56	0.64	1.5	23.7
102	11POPH102	120.60	3.5	14	2.8	19.3	256.3	73.3	0.51	0.76	1.7	47.9

Entry	**Name**	**Grain yield**			**NCLB**	**EARL**	**PH**	**DMP**	**EPO**	**SHELL**	**EPP**	**SL**
		Relative to control P618	**Mean (t/ha)**	**Rank**								
103	11POPH103	74.66	2.2	95	3.4	19.5	216.3	73.3	0.52	0.70	1.4	28.8
104	11POPH104	102.50	3.0	37	2.8	18.6	256.0	74.5	0.53	0.70	1.7	18.1
105	11POPH105	139.48	4.0	3	3.0	19.4	239.0	74.8	0.53	0.74	1.7	44.6
106	11POPH106	106.12	3.1	33	2.8	20.1	236.8	75.0	0.55	0.69	1.4	3.9
107	11POPH107	79.74	2.3	85	2.9	14.9	223.5	73.0	0.54	0.76	1.6	18.5
108	11POPH108	137.07	4.0	4	2.4	19.1	238.0	76.0	0.57	0.75	1.7	54.4
109	11POPH109	122.67	3.6	11	2.6	18.2	242.3	71.3	0.57	0.65	1.7	34.7
110	11POPH110	103.88	3.0	36	3.3	19.0	218.5	71.0	0.49	0.73	1.3	10.1
111	11POPH111	131.03	3.8	7	2.9	19.2	224.5	72.8	0.53	0.78	1.7	13.5
112	11POPH112	95.09	2.8	59	3.1	19.7	231.3	70.0	0.47	0.70	1.2	30.1
113	11POPH113	75.78	2.2	93	3.0	17.4	224.8	71.0	0.49	0.73	1.6	32.6
114	11POPH114	84.31	2.4	76	3.0	18.9	237.0	72.3	0.51	0.76	1.4	2.5
115	11POPH115	116.12	3.4	17	3.1	21.5	257.8	70.0	0.56	0.75	1.4	19.0
116	11POPH116	68.71	2.0	101	3.1	19.9	235.0	72.8	0.45	0.73	1.2	34.1
117	11POPH117	50.43	1.5	119	3.1	18.8	241.0	72.5	0.50	0.72	1.3	21.3
118	11POPH118	94.40	2.7	60	3.1	20.5	220.3	70.5	0.52	0.76	1.4	34.8
119	11POPH119	91.47	2.7	66	2.9	20.3	203.0	72.5	0.49	0.78	1.3	21.7
120	**P618**	**101.03**	**2.9**	**42**	**3.3**	**20.1**	**233.0**	**71.3**	**0.48**	**0.74**	**1.3**	**43.8**

Appendix 3: Means for popping quality traits of 120 hybrids

Entry	Name	Rank	Flake volume	Popping fold	Unpopped kernels (No.)	Kernels /10g	Moisture content (%)	Quality score
13	11POPH13	1	1287.5	25.8	29.1	65.8	13.1	2.2
81	11POPH81	2	1250.0	25.0	47.4	67.1	12.7	1.7
82	11POPH82	3	1231.3	24.6	32.5	65.3	12.9	1.6
24	11POPH24	4	1218.8	24.4	34.1	55.8	13.1	1.3
33	11POPH33	5	1218.8	24.4	46.8	64.0	12.6	1.6
37	11POPH37	6	1218.8	24.4	47.4	65.3	12.9	2.2
21	11POPH21	7	1212.5	24.3	44.8	65.8	12.8	1.5
19	11POPH19	8	1201.6	24.0	35.9	65.4	12.8	1.5
110	11POPH110	9	1187.5	23.8	20.9	60.6	12.9	1.8
43	11POPH43	10	1184.4	23.7	45.5	65.0	13.2	2.2
14	11POPH14	11	1175.0	23.5	51.9	68.6	13.0	1.2
17	11POPH17	12	1171.9	23.4	52.4	66.4	13.0	2.0
117	11POPH117	13	1171.9	23.4	38.7	63.4	12.9	2.0
22	11POPH22	14	1168.8	23.4	55.3	65.4	13.0	1.8
116	11POPH116	15	1168.8	23.4	64.0	72.4	12.9	1.9
120	P618	16	1156.3	23.1	53.9	64.0	13.0	1.6
11	11POPH11	17	1143.8	22.9	32.8	72.5	13.1	1.5
25	11POPH25	18	1143.8	22.9	26.8	52.5	12.9	1.4
41	11POPH41	19	1143.8	22.9	50.0	74.5	12.9	1.7
80	11POPH80	20	1143.8	22.9	35.9	63.1	12.8	1.6
92	11POPH92	21	1140.6	22.8	67.4	75.8	13.1	1.4
53	11POPH53	22	1137.5	22.8	53.8	67.9	12.9	1.8
72	11POPH72	23	1137.5	22.8	57.1	63.0	13.0	1.7
97	11POPH97	24	1137.5	22.8	43.6	67.9	12.9	1.8
115	11POPH115	25	1137.5	22.8	22.7	58.3	13.0	1.8
5	11POPH5	26	1131.3	22.6	45.1	55.8	12.8	1.5
60	11POPH60	27	1131.3	22.6	52.9	63.0	13.1	1.5
89	11POPH89	28	1128.1	22.6	46.8	58.4	13.1	1.7
73	11POPH73	29	1125.0	22.5	29.6	55.0	12.1	1.9
6	11POPH6	30	1121.9	22.4	45.4	61.6	12.7	1.7
79	11POPH79	31	1121.9	22.4	52.4	64.0	13.1	2.0
112	11POPH112	32	1121.9	22.4	30.9	59.5	13.1	1.5
4	11POPH4	33	1118.8	22.4	49.5	68.5	12.6	2.5
47	11POPH47	34	1115.6	22.3	77.6	71.5	13.0	1.8
51	11POPH51	35	1115.6	22.3	60.6	65.8	12.9	2.2
95	11POPH95	36	1115.6	22.3	46.6	83.0	12.8	2.0
114	11POPH114	37	1115.6	22.3	26.9	63.0	13.0	1.7
15	11POPH15	38	1112.5	22.3	51.7	74.0	12.7	2.2
27	11POPH27	39	1112.5	22.3	55.2	70.9	12.7	2.1
18	11POPH18	40	1109.4	22.2	65.8	67.0	12.9	2.0
12	11POPH12	41	1106.3	22.1	83.7	85.8	13.0	2.5
77	11POPH77	42	1106.3	22.1	62.4	75.0	12.9	1.7

Entry	Name	Rank	Flake volume	Popping fold	Unpopped kernels (No.)	Kernels /10g	Moisture content (%)	Quality score
39	11POPH39	43	1103.1	22.1	35.3	73.5	12.6	3.0
9	11POPH9	44	1096.9	21.9	49.1	75.6	13.0	1.8
83	11POPH83	45	1096.9	21.9	35.4	60.1	12.9	2.0
8	11POPH8	46	1093.8	21.9	62.5	79.0	13.0	2.0
29	11POPH29	47	1093.8	21.9	63.6	83.5	12.9	1.9
78	11POPH78	48	1093.8	21.9	65.8	70.6	12.7	2.0
62	11POPH62	49	1090.6	21.8	29.9	52.4	12.9	1.5
44	11POPH44	50	1087.5	21.8	49.4	66.1	12.9	2.1
31	11POPH31	51	1081.3	21.6	42.6	63.3	12.6	2.2
54	11POPH54	52	1081.3	21.6	35.1	59.8	12.7	1.8
63	11POPH63	53	1081.3	21.6	75.6	79.5	12.8	1.7
88	11POPH88	54	1081.3	21.6	26.1	61.1	13.0	1.8
36	11POPH36	55	1078.1	21.6	46.3	73.9	12.7	2.2
103	11POPH103	56	1071.9	21.4	46.3	69.4	12.8	2.0
94	11POPH94	57	1068.8	21.4	72.1	81.6	12.7	2.7
101	11POPH101	58	1065.6	21.3	49.4	67.3	12.8	2.7
96	11POPH96	59	1062.5	21.3	35.9	64.4	12.9	1.8
118	11POPH118	60	1062.5	21.3	44.4	55.1	12.9	2.0
7	11POPH7	61	1059.4	21.2	46.3	63.0	12.9	1.8
49	11POPH49	62	1059.4	21.2	73.0	77.1	13.1	2.3
93	11POPH93	63	1059.4	21.2	42.9	73.5	12.9	1.7
98	11POPH98	64	1059.4	21.2	30.2	59.5	12.8	1.9
106	11POPH106	65	1059.4	21.2	57.8	72.8	12.9	1.8
107	11POPH107	66	1056.3	21.1	53.9	79.1	12.8	1.8
28	11POPH28	67	1050.0	21.0	62.3	86.6	12.8	1.8
57	11POPH57	68	1043.8	20.9	37.9	59.8	12.8	2.2
90	11POPH90	69	1043.8	20.9	40.3	64.4	12.7	1.9
3	11POPH3	70	1040.6	20.8	56.4	78.3	12.7	1.8
65	11POPH65	71	1037.5	20.8	82.0	77.1	12.8	1.8
2	11POPH2	72	1034.4	20.7	45.4	69.6	12.5	1.8
71	11POPH71	73	1031.3	20.6	37.5	61.1	12.7	1.8
55	11POPH55	74	1021.9	20.4	30.9	57.9	12.8	2.4
59	11POPH59	75	1018.8	20.4	41.3	63.4	12.6	2.4
10	11POPH10	76	1015.6	20.3	45.9	61.9	12.9	2.7
85	11POPH85	77	1015.6	20.3	70.5	77.0	27.4	2.1
86	11POPH86	78	1006.3	20.1	57.0	79.9	12.7	2.3
105	11POPH105	79	1006.3	20.1	24.8	54.0	13.0	1.9
45	11POPH45	80	1003.1	20.1	63.2	73.8	12.7	1.6
46	11POPH46	81	1000.0	20.0	28.1	69.4	12.8	2.1
91	11POPH91	82	1000.0	20.0	72.5	78.4	12.9	2.2
99	11POPH99	83	1000.0	20.0	31.7	56.9	12.7	1.5
104	11POPH104	84	1000.0	20.0	32.7	54.3	12.8	2.1
64	11POPH64	85	996.9	19.9	86.8	76.8	12.7	2.2
48	11POPH48	86	990.6	19.8	84.6	81.0	12.9	2.3

Entry	Name	Rank	Flake volume	Popping fold	Unpopped kernels (No.)	Kernels /10g	Moisture content (%)	Quality score
66	11POPH66	87	990.6	19.8	74.1	79.1	12.6	1.9
70	11POPH70	88	990.6	19.8	41.8	67.8	12.5	2.2
61	11POPH61	89	985.7	19.7	60.7	78.2	12.5	2.1
1	11POPH1	90	981.3	19.6	40.9	61.6	12.8	2.5
32	11POPH32	91	978.1	19.6	83.8	77.3	12.5	1.7
119	11POPH119	92	978.1	19.6	22.6	62.8	12.7	1.2
56	11POPH56	93	975.0	19.5	74.2	68.1	12.6	2.2
52	11POPH52	94	965.6	19.3	60.8	60.0	12.6	2.6
69	11POPH69	95	962.5	19.3	45.9	72.5	12.7	1.6
34	11POPH34	96	956.3	19.1	85.9	83.3	12.4	2.3
58	11POPH58	97	956.3	19.1	45.1	70.3	12.7	2.5
109	11POPH109	98	956.3	19.1	26.8	59.3	12.8	1.9
42	11POPH42	99	953.1	19.1	91.9	89.8	12.8	2.8
74	11POPH74	100	953.1	19.1	34.4	67.3	12.9	2.2
102	11POPH102	101	946.9	18.9	27.8	63.6	12.9	1.9
76	11POPH76	102	928.1	18.6	42.2	59.6	12.9	2.3
40	11POPH40	103	925.0	18.5	97.1	84.5	12.7	3.1
50	11POPH50	104	918.8	18.4	96.7	78.1	12.8	2.0
35	11POPH35	105	912.5	18.3	52.1	74.4	12.4	2.5
75	11POPH75	106	903.1	18.1	28.4	66.9	12.8	1.5
26	11POPH26	107	900.0	18.0	46.8	57.1	12.6	2.4
67	11POPH67	108	893.8	17.9	29.1	61.9	12.7	2.6
30	11POPH30	109	881.3	17.6	54.0	69.3	12.6	2.7
16	11POPH16	110	878.1	17.6	121.0	88.1	12.8	2.8
38	11POPH38	111	878.1	17.6	97.5	82.8	12.4	2.9
84	11POPH84	112	878.1	17.6	94.4	87.9	12.6	2.5
111	11POPH111	113	878.1	17.6	31.6	62.8	12.9	2.1
113	11POPH113	114	871.9	17.4	82.7	80.4	12.7	2.4
100	11POPH100	115	843.8	16.9	68.4	85.3	12.8	2.5
23	11POPH23	116	815.6	16.3	24.8	52.1	12.7	1.7
87	11POPH87	117	809.4	16.2	44.9	68.5	12.6	2.7
20	11POPH20	118	756.3	15.1	29.8	50.0	12.8	2.2
108	11POPH108	119	750.0	15.0	29.3	69.0	12.7	2.3
68	11POPH68	120	734.4	14.7	18.8	49.1	12.9	2.3