Breeding investigations of maize (*Zea mays* L.) genotypes for tolerance to low nitrogen and drought in Zambia

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Abstract

Low soil nitrogen (N) and drought impede maize production in the small-scale farming sector in Zambia; and adoption of new cultivars with improved tolerance might enhance production. This study: a) assessed farmer preferences for maize cultivars; b) determined genotype x environment interaction effects among popular maize cultivars under contrasting soil fertility levels and; c) investigated landraces for tolerance to low N and drought using S_1 selection. The study was carried out in Zambia from 2004-07.

Farmer preference influencing the adoption of maize cultivars was investigated using both formal and informal surveys in Luangwa, Chibombo and Lufwanyama rural districts representing the three agro-ecological regions of Zambia. Focus group discussions and personal interviews were used to collect data on issues that affected maize production in these areas. It has been found that although farmers perceived landraces to be low yielding, they believed that they were superior to improved cultivars for: tolerance to drought; tolerance to low soil fertility; grain palatability; grain storability; and poundability. The need for food security, their inability to apply fertiliser, and their need for drought tolerant cultivars significantly ($p \leq 0.05$) influenced farmers in adopting cultivars. The farmers would readily adopt cultivars that address these concerns. The predominant use of certain landraces (76%) reflected their superiority in meeting some of these needs.

The performance of nine popular cultivars (three for each of hybrids, OPVs and landraces) under contrasting levels of soil fertility, across six environments (ENVs) in the three agro-eological regions, was evaluated. An ENV was defined as season x location combination. The fertilizer treatments were full fertilization, basal dressing, top dressing and nil fertilization. The cultivars exhibited significant non-crossover type of genotype x fertilisation interaction effects at three ENVs, while the genotype x fertilisation interaction effects, were non-significant at the other three ENVs. The cultivars exhibited dynamic stability by increasing grain yield (GY) when fertilization was increased. Landraces yielded higher than all open pollinated varieties and were generally higher yielding than two hybrids. Based on average rank for GY, the five highest yielding cultivars were MRI724, Gankata, MM603, Kazungula and Pandawe. Superiority of landraces revealed their genetic potential for GY under low soil fertility and they should be used as germplasm in developing cultivars targeting such environments.

Ninety-six local landraces were selfed to generate S_1 lines (2004/05 season) which were crossed to a tester (2005/06 season). Testcrosses were evaluated under optimal, low N, and drought conditions (2006/07 season). Data on GY, anthesis-silking interval, number of ears per plant, leaf senescence, leaf rolling, tassel size and grain texture were recorded in all the trials during the study period. Testcrosses, their S_1 parents and landraces that were superior under low N, drought, optimal conditions and across environments were identified; these should be used to develop varieties targeted to a particular environment. Selection for tolerance to drought also selected for tolerance to low N. Selection for low N tolerance also selected for GY under drought and optimal conditions. Therefore, in selecting for tolerance to abiotic stresses, use of optimal and managed stress environments was effective. The following landraces were superior at 10% selection intensity: LR38, LR84 and LR86 (optimal, low N and drought conditions); LR11, LR35 and LR76 (low N and drought conditions); LR12 (optimal and drought conditions); LR40 and LR93 (low N conditions only); LR79 (drought conditions only) and; LR74 and LR85 (optimal conditions only). These landraces should be used as source germplasm targeting respective environments.

Significant ($p \leq 0.05$) positive general combining ability effects for GY under both low N and drought conditions were found implying that additive gene action conditioned GY under the abiotic stresses. The heritability for GY under low N (0.38), and drought (0.17) conditions, was low suggesting that selection based on GY alone was not effective. The genetic correlation for GY between optimal, and either low N (r_G=0.458), or drought (r_G = 0.03) environments, was low ($r_G < 0.5$) suggesting that indirect selection would not be effective either. Therefore, use of secondary traits for selection is discussed.

The study established that most farmers depended on local landraces for seed and would adopt low input improved varieties that yield higher than the landraces. Some landraces were found superior to some improved cultivars under contrasting fertilisation regimes. The study also found that landraces had genetic variation for tolerance to low N and drought. Landraces, S_1 lines and testcrosses superior under low N, drought, optimal conditions and across environments were selected and they should be used to develop cultivars targeting respective environments. Policy implications of these results are discussed.

Declaration

The thesis study was carried out in the African Centre for Crop Improvement (ACCI), in the School of Biochemistry, Genetics, Microbiology and Plant Pathology, University of KwaZulu-Natal, Pietermaritzburg Campus, under the supervision of Professor P. Tongoona and Dr. J. Derera.

The research presented in this thesis represents original work by the author and has not been otherwise submitted in any form for degree or diploma to any university. Where use has been made of the work of others it is duly acknowledged in the text.

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Dedication

To my father, Lorent, whose hard work has always inspired me to move on.

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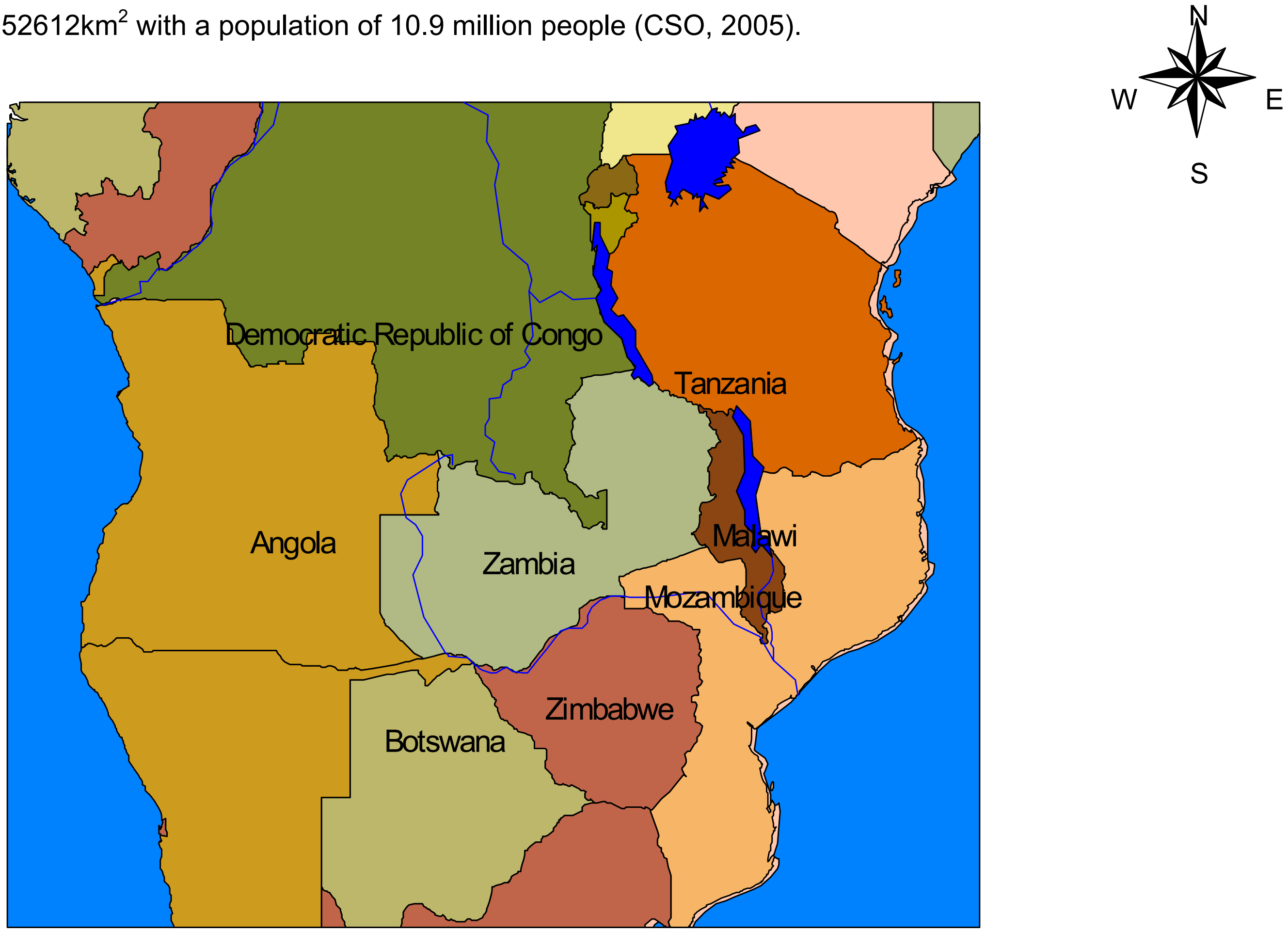
List of Abbreviations

AD	Anthesis date
ASI	Anthesis-Silking Interval
CHI	Chilanga
DTI	Drought tolerant index
EPP	Number of ears per plant
GCA	General Combining Ability effects
GE	Genotype x environment interaction effects
Gtext	Grain texture
GY	Grain yield
H^2	Broad sense heritability estimate
Hh	Household head
LNTI	Low N tolerant Index
LR	Landrace
Lroll	Leaf rolling
Lsene	Leaf senescence
LUA	Luangwa
MAS	Marker Assisted Selection
MASA	Masaiti
PRA	Participatory Rural Appraisal
r_G	Genetic correlation
S_1 line	Selfed first generation line
SD	Silking date
SI	Selection Index
TC	Testcross

Introduction to Thesis

1. Zambia and its agro-ecology

Zambia lies between latitudes 8-18° South and longitude 22-33° east and occupies a near central position in the southern African sub-continent (Fig. 1). The country is 752612km^2 with a population of 10.9 million people (CSO, 2005).

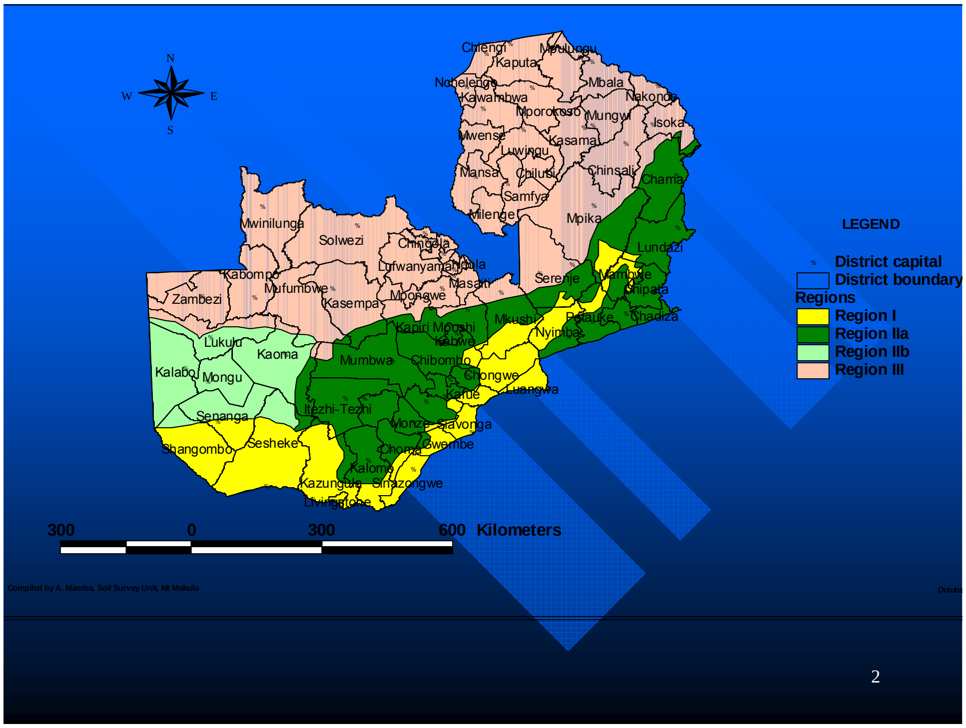


Source: UNZA (2007)

Fig. 1: Geographical location of Zambia in southern Africa

The country is sub-divided into three agro-ecological regions defined according to climatic characteristics with rainfall as the main factor (Bunyolo et al., 1997). Region I lies in the lowlands, 300-900m above sea level, receives rainfall of up to 800mm per annum over 80-120d; and experiences drought of about 5 ten-day periods per growing season. Region II, 900-1300m above sea level, receives 800-1000mm over about 100-140d; and experiences drought of about 1-3 ten-day periods. Region III lies about 1100-1700m above sea level; receives over 1000mm of rain over 120-150d in a year; and rarely experiences any drought (Bunyolo et al., 1997).

The high rainfall areas are concentrated in the northern part of the country (Fig. 2). Region IIa has fertile loamy soils, while Region IIb is sandy. According to Muchinda (1985), average temperatures during the rainy season, October to April, when much of the maize is grown, are about 24˚C in Region I (e.g., Livingstone) and 22˚C in Regions II (e.g., Mt. Makulu) and III (e.g., Mansa).



Source: ZARI (2007)

Fig. 2: Agro-ecological Regions of Zambia

Zambia has savanna type vegetation with soils generally well drained and ranging from clay to loamy and sandy soils (Bunyolo et al., 1997) in each of the agro-ecological regions. However, moist savanna soils have a low nutrient content (Vanlauwe et al., 2001) and require added nutrients to increase maize yields.

2. Importance of maize in Zambia

Maize (*Zea mays* L.) is the most important food crop in Zambia and is produced in all the nine provinces of the country. It is used primarily for human consumption as porridge, nshima (local name), or fresh green maize (Mungoma, 1997) and is eaten every day in most households.

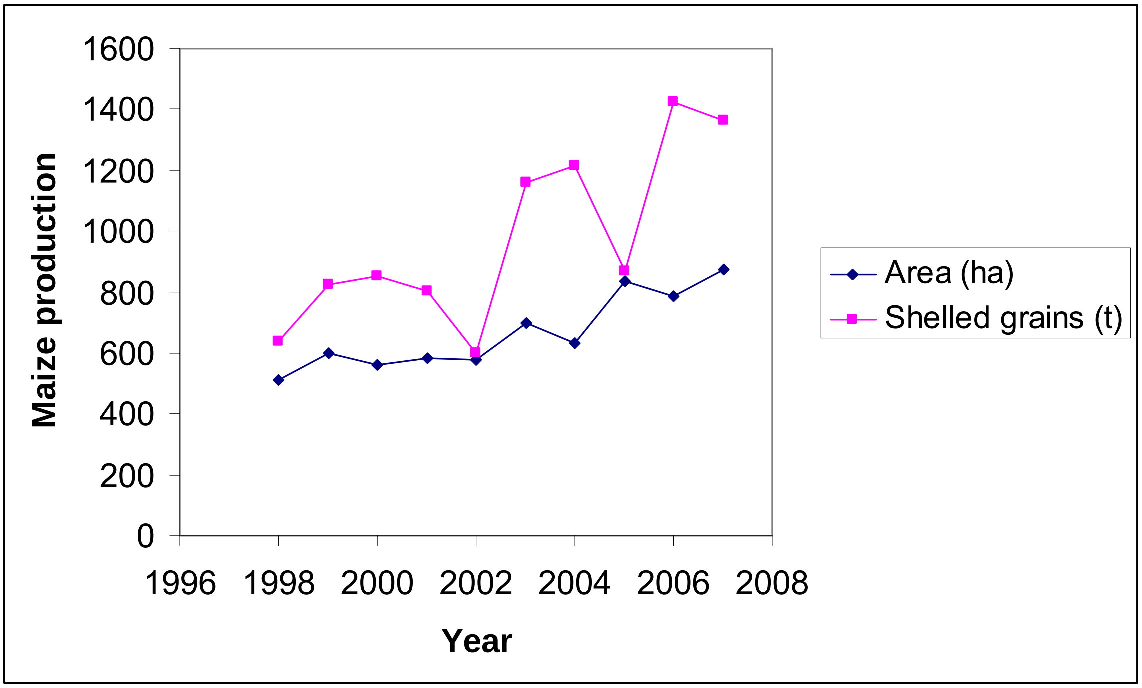
According to CS0 (2006a), about 65% of the households in Zambia are agricultural; of these about 84% are located in rural areas (Table 1). Over 90% of agricultural households are small-scale farmers; 69% cultivate only up to 2 ha (CSO, 2006b). About 86% of the agricultural households grow maize while only 9% grow millet, the second most widely cultivated cereal in the country (CS0, 2005).

Table 1: Percentage of agricultural households growing major cereals in Zambia

			Percentage of the agricultural households			
Province	Total households†	Agricultural households†	Growing maize	Growing Sorghum	Growing Millet	Growing rice
Central	207 243	157 940	95	8	7	1
Copperbelt	311 712	116 144	97	6	1	0
Eastern	290 224	253 540	99	1	2	2
Luapula	171 659	148 176	50	1	4	2
Lusaka	309 949	45 655	99	2	0	0
Northern	275 395	238 465	69	4	34	5
North Western	126 107	103 017	90	3	1	0
Southern	252 423	178 589	96	7	3	0
Western	166 219	136 499	92	6	7	6
Total	2 110 931	1 378 025	86	4	9	2

Data Source: †CSO (2006a); CSO (2006b)

Between 1997 and 2007, the area under maize production increased from 510372ha during the 1997/98 season to 872812ha during the 2006/7 season; while the average grain yield ranged from 1.25-1.93t ha^{-1} over the same period (MACO, 2007). Zambezi and Mwambula (1997) reported that improved varieties of maize yielded over 10t ha^{-1} under research station conditions in southern Africa but < 1t ha^{1} under farmer conditions. The wide gap between grain yields of maize at research stations and that obtained by small-scale farmers is a matter of concern. However, the area under maize cultivation has continued to increase (Fig. 3) and explains its continued importance in Zambia.



Data Source: MACO (2007)

Fig. 3: Maize production ('000 tons) in Zambia between 1997-2007

3. Major factors limiting maize yields in Zambia

Drought and low nitrogen have been reported as the two major constraints in maize production by small-scale farmers in southern Africa (Zambezi and Mwambula, 1997; Banziger et al., 1999). Some farmers fail to irrigate during the drought periods to mitigate the effects of water deficiencies while others fail to apply nitrogen fertiliser to support plant growth and development. Drought may cause yield losses of up to 60% (Edmeades et al., 1999) in southern Africa. Logrono and Lothrop (1997) reported that low nitrogen caused yield losses of up to 50% in Asia. Waddington and Heisey (1997) found that nitrogen deficiency was a widespread constraint to small-scale farm productivity throughout southern Africa. Farmers were unable to apply the fertiliser, due to lack of financial resources and availability of product (Mungoma and Mwambula, 1997).

4. Efforts to enhance maize production

In order to increase maize production among small-scale farmers, the government of Zambia (GRZ) and some non-governmental organizations (NGOs) distributed maize seed and fertiliser to small-scale farmers across the country (MACO, 2005). However, this support fell short of reaching all the farmers and the intervention was largely unsustainable. The GRZ and some NGOs also promoted conservation farming among the farmers. According to Mulenga (2001), conservation farming practices, such as crop rotation, contour farming, mulching, use of cover crops, zero tillage and green manure are promoted in Zambia to enrich and protect the soil from further degradation, and increase farm productivity. However, the practices are often too labour intensive and are rarely practised on a large scale.

Jeranyama et al. (2000) reported that the rising real price of purchased inputs in Zimbabwe drove small-scale maize production towards applying lower levels of inorganic fertiliser. They found that legume intercrops were a source of plant nitrogen that could be produced locally and offered a practical complement to inorganic fertilisers. They, therefore, recommended intercropping maize with annual legumes; and the application of small amounts of inorganic fertiliser as an alternative strategy to meeting the nitrogen needs on maize fields of small-scale farmers. However, intercropping affects the yield of the second crop, a situation discouraging farmers from adopting the practice. Moreover, acquisition of even small amounts of inorganic fertilisers may still be a problem to the majority of small-scale farmers in Zambia, due to its limited availability and affordability in rural areas.

Ma et al. (1999) reported that manure treatments produced grain yields equal to, or slightly greater (6–13%) than, the fertiliser treatment. They found that dairy manure application increased N uptake and grain yield of maize. However, use of organic manure was only feasible on a small-scale vegetable type farming, and not on maize fields requiring large quantities of manure which may be too expensive to farmers. Application of manure may also introduce weeds that could be costly to farmers to procure and transport.

In a study to determine the relationship between relative maize nitrogen deficiency and time of nitrogen application, Binder et al. (2000) found that the greater the nitrogen deficiency, the earlier nitrogen had to be applied to obtain maximum grain production. In Zambia, fertiliser application recommendations for maize were available and were based on tests carried out on soils sampled throughout the country (MACO, 2002). Farmers were generally aware of the appropriate time to apply fertilisers in order to maximize maize production. However, this may not be an effective solution for small-scale farmers lacking financial resources to purchase fertilisers.

Although maize production that uses high-yielding varieties with high fertiliser input contributes to yield increase in both developed and developing countries, discharges of fertilisers (nitrate) cause surface and ground water pollution (Ding et al., 2005). Breeding maize varieties with high yield under low nitrogen could reduce environmental pollution and increase the economic efficiency of nitrogen use. Maintaining productivity under low nitrogen could aid breeding for future yield increase, under low N.

In order to contribute to increasing maize production among the predominantly small-scale farmers in Zambia, high yielding varieties that are tolerant to drought and low nitrogen should be developed. This requires an understanding of the various maize characteristics when a genotype is grown under such stresses. The varietal development should also incorporate farmer preferences, which are important in influencing their decisions to adopt a variety.

5. Understanding farmers' preferences for a maize variety

Over many generations, farmers developed landraces (local) varieties by altering the genetic makeup of the crops they grow through selection mainly for ear and kernel characteristics (Louette and Smale, 2000). This has dramatically changed the domesticated maize plant compared to its original form. However, such varieties generally have low yield but are still widely grown by resource poor farmers. Understanding farmers' preferences and experience in maize production could not only explain the continued use of their local cultivars (landraces), but also complement the development of farmer preferred varieties that address some of their limitations in cultivating maize. Small-scale farmers face numerous limitations when cultivating maize. To develop an appropriate variety, it is crucial for a breeder to understand the crop environment at a farmer’s field. According to Langyintuo et al. (2003), farmers adopt a variety when they are well informed of it, the variety is appropriate and its use is affordable.

During the 2003/04 season, about 68% of agricultural households planted local landraces in Zambia (CSO, 2005) despite the availability of 155 released maize varieties (SCCI, 2007). Table 2 shows that the majority of maize growers planted local landraces in all nine provinces. This probably suggests either that farmers cannot afford, access quality seed or do not appreciate, the value of improved varieties and calls for further research on this issue.

Table 2: Percentage of agricultural households who planted different types of seed across the country during the 2003/04 agriculture season

Province	All types of maize varieties	Local landraces	Improved varieties
Central	95	67	35
Copperbelt	97	73	28
Eastern	99	92	22
Luapula	50	42	9
Lusaka	99	57	51
Northern	69	58	12
North Western	90	81	12
Southern	96	54	47
Western	92	74	23
Total	86	68	25

Source: CSO (2005)

Use of improved maize varieties was highest in Lusaka province (Table 2), probably because it is located near to sources of seed and other inputs such as fertiliser, irrigation and chemicals. Despite much of the seed production and input provision being concentrated in areas along the railway line passing through Southern, Lusaka, Central and Copperbelt provinces, the low use of improved seed varieties in some of these provinces suggests that the problem may be not only that of supply.

6. Outline of the research study

This section outlines the study to provide the reader with the scope of the research. It briefly describes the specific study areas and specifies the chapter under which the work is reported in the thesis.

a) Literature review

The literature is reviewed to describe, summarize, evaluate, clarify and/or integrate information related to the breeding of maize for tolerance to low nitrogen (N) and drought in Zambia. The review is covered in Chapter 1.

b) Assess farmer preferences on maize varieties

The ultimate aim of a plant breeder is that the developed variety should reach farmers. A variety that meets farmers' expectations may be readily adopted by farmers. It is therefore important that a breeder understands farmer preferences and the crop environment in order to optimize the breeding strategy. In this study (Chapter 2), a participatory rural appraisal (PRA) and a formal survey were carried out in Zambia to assess farmer preferences for maize varieties, to obtain information about farmer perception of maize and to document the crop environment under small-scale farming. The hypothesis tested was that there is a low adoption of improved maize varieties because the varieties failed to meet farmer expectations.

c) Determination of genotype x environment interaction effects (GE)

A farming environment usually changes over time with variation in weather and soil, and the stability of grain yield of a variety across different environments is important if a variety is to receive general acceptance by farmers. Some released maize varieties and popular local landraces were assessed under different soil fertility levels in each of the three agro-ecological regions of Zambia to establish their suitability under different soil fertility levels simulating farmers' conditions in Zambia. The hypothesis tested is that widely grown maize cultivars are stable in performance across different fertility levels and environments in Zambia. This work is covered in Chapter 3.

d) Selection for low nitrogen tolerance in S_1 lines derived from local maize landraces

The local landraces grown under suboptimal conditions by small-scale farmers over generations should be endowed with genes conferring tolerance to low N stress. In this study (Chapter 4), local maize landraces were selfed, resultant S_1 lines were crossed to a tester and the testcrosses were evaluated under low N (stress) and high N conditions (non stress) to identify genotypes superior under low N. The hypothesis tested was that there is adequate genetic variation among local maize landraces for tolerance to low N, which could be improved by selection.

e) S_1 selection of maize landraces for drought tolerance.

A genetic study of grain yield and some secondary traits will provide information to improve the identification of genotypes with alleles for tolerance to drought. Local maize landraces were selfed, the progeny S_1 lines were crossed to a tester, and the testcrosses were evaluated under drought (stress) and well watered conditions (non stress) to select genotypes superior under drought (Chapter 5). The hypothesis tested was that there is adequate genetic variation among local maize landraces for tolerance to drought, thus allowing improvement in drought tolerance by selection.

f) Overview

In concluding the thesis, major findings of the research are reviewed and implications for breeding are discussed. This is covered in Chapter 6.

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Chapter 1: Literature Review

1.1 Introduction

The review of literature under this chapter is meant to describe, summarize, evaluate, clarify and/or integrate information related to breeding of maize for tolerance to drought and low nitrogen (N) in Zambia. The review also identifies dimensions of current work in the areas under study and provides an up to date comprehensive review of methods and results. The review covers: i) cultivation requirements of maize; ii) farming systems under which maize is grown; iii) gene action conditioning grain yield (GY) under low N and drought; iv) breeding for tolerance to low N and drought and; v) adoption of maize varieties.

1.2 Cultivation Requirements of Maize

Maize is grown all over the world from about latitudes 55° North to 40° South and from sea level to 3 800m altitude. It has adapted to a wide range of environments with its growing period ranging from 65d in the lowland tropics, to approximately 12 months in the tropical highlands (Fischer and Palmer, 1984). It performs well on well-drained fertile soils in areas with moderately high temperatures and adequate, but not excessive rainfall (Jugenheimer, 1976; Mungoma, 1997). It requires about 450-600mm of water during its growing cycle and yields about 20kg ha^{-1} of grain for each mm of water, giving an average potential yield of 9-12t ha^{-1} (Pendleton, 1979). With minimum average rainfall of about 600mm season^{-1}, Zambia receives enough rain to support maize production and achieve high yields.

For normal growth, maize requires essential elements, of which nitrogen (N), phosphorous (P) and potassium (K) are the most important. The minimum levels of these three elements required in dry soil to support maize production are 3.0% N, 0.25% P and 1.9% K (Mohr and Dickson, 1979). Much of the soil in Zambia is of savanna type and contains very small amounts of N because much of the nutrient is lost through leaching and/or de-nitrification (Vanlauwe et al., 2001). Low organic matter content, incomplete decomposition of organic matter and water logging also contribute to natural levels of N deficiency in soils (Simpkins and Williams, 1984). Under N deficiency, plant leaves turn yellow, stalks become thin and tall, while the grain gets fewer and smaller than under well fertilised conditions (Mohr and Dickson, 1979; Clark, 1982). Although maize requires N throughout its growth cycle, its N requirement increases sharply at about four weeks after planting, when the maize growing point switches from producing leaves, to producing the terminal reproductive structure, and the tassel is initiated (Mohr and Dickson, 1979). In order to enhance reproduction of the plant, N fertiliser is applied at this stage. About 15-18kg of N is required for the production of 1t of maize grains (Mohr and Dickson, 1979). In Zambia about 112kg ha^{-1} of N is recommended for application to maize and this could enable farmers to realize grain yields of about 6-8t ha^{-1} (Wellving, 1984). Some N is also naturally made available to plants through decomposition of organic matter in the soil. However, the general N recommendation may not be appropriate for semi-arid areas in Region I where soils generally lack moisture. Region I receives less rain and experiences higher temperatures than the other regions, hence the low soil moisture. Therefore, the limited available soil moisture is inadequate to dissolve the applied inorganic fertilisers which remain unavailable to plants. Shamudzarira and Robertson (2002) found that moderate rates of about 30kg N ha^{-1} gave greater N response than lower rates (15kg N ha^{-1}) in semi-arid areas in Zimbabwe. The recommended rates may be too high in the dry Region I of Zambia.

A maize plant optimizes its growth at 24-30˚C (Pendleton, 1979). According to Muchinda (1985), average temperatures range from 20-26˚C, during summer when much of the maize is grown in Zambia. This is close to optimal temperature for maize growth and development and confirms the suitability of maize cultivation in Zambia.

1.3 Farming systems under which maize is grown

About 58% of Zambia's total area is classified as having medium to high agricultural potential and less than half of the arable land is under cultivation (CSO, 2005). The non-arable land is either covered by water (rivers and lakes), or is too rocky for crop production. However, such rocky areas are useful for livestock production. The main sources of cash for farmers are remittances by relatives in towns, cattle sales, small ruminants, tobacco, cotton and food crop (maize and pulses) sales. Cattle are kept for meat, milk, payment of bride price, ploughing, breeding, farm manure and sale. In spite of the scattered settlement pattern, community institutions and market linkages are available.

Maize is cultivated in all three agro-ecological regions by all types of farmers with over 90% being small-scale (CSS, 2001), cultivating up to 5ha (Gethi, 2003). According to CSO (2006a), 96% of farmers in Zambia cultivate less than 5ha and 69% cultivate less than 2ha. About 15% of the maize (220000t) is produced by large scale farmers (CSO, 2005).

Socio-economic differentiation is high and a farming constraint for small-scale farmers is limited access to inputs. These farmers cannot afford fertiliser, irrigation and agricultural chemicals to enable them to exploit the potential of their purchased improved seed. In addition, the purchase price of fertiliser, given its high price relative to grain price of maize, does not make economic sense to small-scale farmers (Mungoma and Mwambula, 1997). Therefore, small-scale farmers depend on the seeds of local unimproved indigenous varieties for planting. These are saved from a previous harvest or purchased at a low cost within their communities (CSO, 2005). However, the farmers obtain low yields of about 1.79t ha^{-1} (CS0, 2006b) when either local or improved seeds are used, although under high input conditions, yields of about 10t ha^{-1} or more are realized (Zambezi and Mwambula, 1997). Maize yields in Zambia have fallen and soil fertility is also declining, and smallholder farmers are reverting to extensive production practices where farmers cut and burn trees to produce ash which is used as fertiliser (Siacinji-Musiwa, 1999). It is not uncommon for the government of Zambia (GRZ) to provide relief and supplementary food requirements to the rural population. Among the main causes of vulnerability are drought and a lack of N fertilisers (Zambezi and Mwambula, 1997). About 88% of the maize is cultivated without fertiliser and on average, about 40-60% and 20-40% of a rainy season is under drought in agro-ecological Region I and II, respectively (Bunyolo et al., 1997; CSO, 2007). The low crop production contributes to the poverty which stands at an average country level of 68% and 79% among small-scale farmers in rural areas (CSO, 2005). Here poverty is defined as living below the mean income group (relative poverty line).

1.4 Low nitrogen and drought under maize cultivation in Zambia

Low nitrogen and drought are the most limiting factors to maize production in Zambia because most farmers are resource poor and cannot afford fertiliser or irrigation (Mungoma and Mwambula, 1997; Zambezi and Mwambula, 1997). Although 95% of the total fertiliser applied to various crops in Zambia during the 2005/06 season was applied to maize (CSO, 2007), this represented only 21.7% of the fertiliser required for cultivation of maize during the season. Therefore, much of the maize was cultivated under low soil fertility and resulted in an average yield of 1.82t ha^{-1} (MACO, 2007). Drought was a common problem in agro-ecological Regions I and II.

1.4.1 Low nitrogen and grain yield

Poor soil nutrient content may result from degradation processes such as dispersion, infiltration and run-off occurring as a result of water erosion (Arriaga and Lowery, 2003; Norton et al., 2003). This leaves the soils too depleted to support the cultivation of maize without additional fertilisation. In Zambia, nutrient content of soils is too low for cultivation of maize and fertilisation is required (Bunyolo et al., 1997). Vvarieties that tolerate low soil N fertility may achieve yields of about 15-25% of a well fertilised crop (CIMMYT, 1999). Intolerant varieties yield less than 1t ha^{-1} under low soil N conditions.

In order to achieve high yields, N is applied to a maize crop. Nitrogen is important in maize production as it promotes vegetative growth, maximizes both kernel initiation and kernel set, and is also key in the establishment and filling of the kernel sink (Below, 1997). The main role of P in maize production is for seed development and stalk health. Potassium improves the plant’s ability to naturally resist diseases and influences the uptake of several other plant nutrients (Zulu and Phiri, 1997). In an experiment to characterize maize S nutritional status and determine maize response to S on farmers' fields in Malawi, Weil and Mughogho (2000) found that maize yields showed N x S interaction effects and that there were no responses to S unless N was also supplied. This shows the importance of making fertiliser blends available to small-scale farmers. Different fertiliser blends are available in Zambia, and production of specific blends on demand is also possible. However, poor marketing and low affordability limit farmer access to the fertilisers.

Nitrogen deficiency is the most severe and widespread constraint to small-scale farm productivity in southern Africa (Waddington and Heisey, 1997). According to Bruns and Abel (2003), N deficiency interferes with protein synthesis and therefore reduces the general growth of maize. Deficiency in N causes poor plant development and reduces maize grain yield (GY). Under low N, maize reduces its shoot biomass and harvest index (Sadras and Calvino, 2001; Calvino et al., 2003). Leaves of plants turn pale yellow from bottom to top and severe deficiency may delay flowering, shorten grain filling period and early senescence (Clark, 1982). Its deficiency affects different yield-determining factors resulting into reduced leaf area, reduced leaf stay-green resulting into low photosynthesis rate and high ear abortion (Banziger et al., 2000).

Genotypes with a short anthesis-silking interval (ASI) and a high number of ears per plant (EPP) are efficient in remobilizing N from the stover to the grain, particularly during the early stage of embryo development thereby reducing embryo or ear abortion (Gallais and Coque, 2005). Anthesis-silking interval has moderately high heritability and was correlated with GY under low N conditions (Banziger and Lafitte, 1997), and selection for low ASI improved yield under the stress (Mungoma and Mwambula, 1997). However, Edmeades et al. (1997) found that ASI only explained 25-35% of variation in GY and could not be used alone. Vasal et al. (1997) observed that in selecting for tolerance to low N, ASI and EPP were effective and agreed with Lafitte and Banziger (1997), who found that in addition to these, leaf senescence (Lsene) was also important. Banziger et al. (2000) reported that the information on GY, EPP, ASI and Lsene were important in identifying superior genotypes under low N. Small-scale farmers selected their seeds based on grain texture (Gtext) and claimed that their local cultivars (landraces) were superior to improved ones in tolerating low N (Chapter 2). This study evaluated GY, EPP, ASI, Lsene, leaf rolling (Lroll), tassel size (Tsize) and Gtext for their relevance in selecting genotypes that tolerated low N.

1.4.2 Drought stress and grain yield

Drought is a situation when there is insufficient soil moisture to meet the needs of a crop at a particular time; this has been a major factor limiting maize production in Zambia (Mungoma and Mwambula, 1997). Water deficiency limits the medium of transport for nutrients, hormones, assimilates, and organic molecules from the soil to the root and within the plant (Ehlers and Goss, 2003). Although water deficiency during any period of the growth of a maize plant reduces GY, the decline is greatest when the deficit occurs at flowering (Bosch et al., 2004; Campos et al., 2006). It inhibits photosynthesis and reduces the carbohydrate stream in the ovaries (Zinselmeier et al., 2000). At flowering, the sink capacity for ears is weak and the low supply of carbohydrate leads to kernel abortion, barrenness and general growth reduction thereby increasing the ASI (Bruce et al., 2002; Campos et al., 2006). Drought results in the accumulation of abscisic acid in leaves where it causes Lroll, stomatal closure and accelerates Lsene (Banziger et al., 2000). Therefore, tolerance to drought at flowering is critical.

Plant efficiency can be measured by its ability to allocate most of the photosynthates toward the formation of grain (Guei and Wassom, 1996). Traits such as plant height, ear height, leaf area, and leaf number affect photosynthetic efficiency of maize plants (Moss and Musgrave, 1971). Other important traits related to efficiency, are Tsize and Lsene of a plant, especially during grain filling. Tassel size affects GY, either physiologically by competition for photosynthates, or physically by a shading effect (Grogan, 1956; Hunter et al., 1969; Mock and Schuetz, 1974). Studies have shown that plants that partition more photosynthates toward the formation of large tassels may have smaller ears, which decreases yield (Hunter et al., 1969). Selection of plants with small tassels is generally believed to improve GY in maize. However, ability to produce a large tassel under stress may also explain a plant's ability to withstand stress and partition resources towards the production of a tassel. Grain yield and its component EPP show dependence on ASI, and the genetic correlation between GY and ASI under drought is high ($r > 0.5$), suggesting that ASI is a visual indicator of underlying processes affecting reproductive success (Parsons, 1982; Mungoma and Mwambula, 1997). Grain yield was also reported to be strongly correlated with ASI by Chapman and Edmeades (1999). Therefore, GY, EPP, ASI, Lsene, Lroll and Tsize (in that order) are considered important in identifying superior genotypes under drought (Lafitte and Banziger, 1997; Banziger et al., 2000). Small-scale farmers selected their seed based on Gtext and claimed that their local cultivars were superior to improved ones for tolerating drought (Chapter 2). This study evaluated GY, EPP, ASI, Lsene, Lroll, Tsize and Gtext for their relevance in selecting genotypes that tolerated drought.

1.5 Gene action and yield

Knowledge of gene action that conditions GY under specific conditions is important in enhancing the development of appropriate crop varieties for respective environments. This section reviews gene action conditioning GY under low N and drought conditions.

1.5.1 Gene action conditioning grain yield under low N

Limited information is available regarding gene action for different characteristics under low N conditions. Reports in the literature vary concerning the type of gene action important for GY under low N conditions reported in literature. Medic et al. (2004) reported that additive gene action was important. Betran et al. (2003) found that it was the non-additive gene action that was important and this was in agreement with Beck and Willcox (1997). Maseka et al. (2006) found that non-additive action was slightly higher than additive gene action under low N conditions. Collectively, these studies have shown that many N use traits are under genetic control and that physiological processes limiting yield differ according to the level of N available in the soil. Therefore, genotypes that tolerate low N could be identified and improved. Beck and Willcox (1997) also reported significant crossover type interaction effects between general combining ability (GCA) effects of lines under low N, when compared to those under high N conditions. This implies that genotypes differ in their response to low and high N conditions.

The relative importance of heredity in determining phenotypic values is called the heritability of the character (Falconer and Mackay, 1996). A high heritability implies that the genetic variation for a trait can be precisely assessed from phenotypic observations (broad sense) (Banziger and Cooper, 2001). Heritability of GY generally decreases under lower yielding conditions (Banziger et al., 1997; Banziger and Cooper, 2001). Moderate broad sense heritabilities were found by Banziger and Lafitte (1997) for GY, ASI, EPP and Lsene under low N. Therefore, selection of superior genotypes based on GY alone or one secondary trait cannot be effective. When information of secondary traits was combined, selection efficiency improved by 14% over selection based on GY alone under low N (Banziger and Lafitte, 1997). This means that combining information of secondary traits in a selection index was effective.

1.5.2 Gene action conditioning grain yield under drought

Upon reviewing different literature on gene action that conditioned GY under drought, Dass et al. (1997) reported that scientists do not agree on the relative importance of additive and dominance gene action under the stress. However, Betran et al. (2003) later found that the additive effects for GY were more important than the non-additive gene action under drought. They also observed that the importance of additive effects increased with increasing drought stress implying that all germplasm in a breeding programme should possess alleles for drought tolerance for selection to be effective. It implies that both parents of a hybrid should possess drought tolerance. These findings agree with those of Beck and Willcox (1997). Guei and Wassom (1996) found that additive gene action was more important in controlling EPP, anthesis day, silking day and ASI than non-additive gene action.

Although GY is an important criterion in selecting genotypes for tolerance under drought, there is wide agreement that its selection under stress is less efficient than under non-stress conditions, mainly because heritability of GY declines under the stress (Byrne et al., 1995; Bolanos and Edmeades, 1996; Vasal et al., 1997; Banziger and Cooper, 2001). Therefore, when selecting for GY under drought conditions, information on secondary traits should also be used. Information on EPP, ASI, Lsene, Tsize and Lroll supplement that of GY in identifying genotypes that tolerate drought (Banziger et al., 2000).

Bolanos and Edmeades (1996) found that the correlation of GY with some secondary traits was low (Tsize, Lsene, Lroll), moderate (ASI) and high (EPP). They also found that genetic correlation between GY and ASI was non-significant under optimal conditions but significant under drought conditions. Guei and Wassom (1996) also found that EPP, silking day and ASI had a high correlation with GY. This implies that secondary traits do not lack genetic variability and could be used in selecting superior genotypes under drought conditions. Information on heritability of secondary traits strengthens breeding strategies under abiotic stress provided they correlated with GY. Edmeades et al. (1997) found that ASI and EPP were highly heritable under drought conditions. They also found high correlations of GY with EPP. However, the correlation between GY and ASI was found to be low under drought conditions.

Heritability of secondary plant traits may be optimized by low competition, enhancing gene fixation and conducting multiple-environment screening (Fasoula and Fasoula, 1997). Under low competition, the single plant phenotypic expression and differentiation increases; the coefficient of variation (CV) is reduced; and the share of genetic variance increases at the expense of the environmental variance and the genotype corresponds more closely to the phenotype. Small-scale farmers generally practice wide spacing that optimizes heritability of traits (such as maturity, plant height). This has probably enabled farmer varieties to retain some useful characteristics over generations. The continued use of local unimproved varieties by small-scale farmers could imply that the local seeds have accumulated some alleles that impart tolerance to common stresses, such as drought or low soil fertility prevalent under their farming systems. Bertoia et al. (2006) found that landraces were superior in stover yield over some commercial hybrids under optimal conditions. Perhaps these landraces have adapted to low population density, because farmers plant in wide spacing. This indicates that yield improvement can be realised by selecting for high yield per plant. Conversely, the landraces might lack tolerance to high plant density stress, suggesting that yield might not be improved by increasing plant population which is the case in temperate environments.

1.6 Breeding for tolerance to drought or low nitrogen

In order to contribute to increasing maize production by small-scale farmers, varieties should be developed that address their major concerns, such as drought and low N. It is envisaged that a variety that tolerates the effects of drought, or low N, will be readily adopted by small-scale farmers and increase their GY.

1.6.1 Source of germplasm

Landraces have resulted from farmer selection over many generations, suggesting that they could have accumulated some alleles for adaptation to the local crop production environment. Azar et al. (1997) found variations in landraces in GY and Gtext, implying that they could be differentiated from one another. In comparative evaluation of landraces and improved varieties under low N, Lafitte et al. (1997) found that improved varieties out-yielded landraces but landraces were superior in grain N concentration. Improved varieties were not consistently superior to landraces in N recovery, aboveground biomass or in the fraction of N partitioned to the grain under low N, which would reflect their efficiency in use of N.

In a study to evaluate maize landraces that could be used as germplasm to enhance forage yield and quality, Bertoia et al. (2006) found that some landraces were superior to commercial hybrids in whole plant yield, indicating their breeding potential. Beck et al. (1997) found that selection for drought tolerance in local 'adapted' populations accelerated breeding progress. They reported results in which three drought tolerant synthetic varieties were developed from S_1 families of local maize populations, and that two superior source populations were created from landraces in west and central Africa. In this study local landraces were used in studying the breeding of maize for tolerance to low N and drought.

1.6.2 Selection for tolerance to low N

Increased stress tolerance is considered by some to be the primary cause of increased grain yielding ability of Corn Belt maize genotypes (Tollenaar and Lee, 2002). Alleles related to stress tolerance are present in most elite maize populations, at a relatively low frequency, and selection under controlled low N was effective in developing varieties that tolerated low N (Vasal et al., 1997). Since yield is controlled by a large number of minor genes, its improvement under low N environment will depend on how the respective genes respond to the stress.

To maximize selection gains under low N, direct selection (i.e. selection environment similar to target environment) should be employed as it was often superior to indirect selection in targeting stress environments (Banziger et al., 1997). Grain yield correlates positively with some traits, but negatively with others (Yan and Wallace, 1995). Therefore, in selecting for GY under low N, a number of secondary traits with significant correlations to it should be taken into account. Use of secondary traits in a selection index may be appropriate. A selection index summarizes the worth of a genotype using information from the various traits. A good secondary trait is genetically associated with GY under stress and its heritability is high and is easy and cheap to measure (Banziger et al., 2000).

Lafitte and Banziger (1997) reported gains in GY of about 3.4% per year under low N when selecting for drought tolerance. They attributed this to reduced ear abortion and delayed Lsene, which are also improved when developing drought tolerance. They also reported a single cycle of selection among half-sib families of a tropical maize population, achieving increased yields under low N but reducing it under high N. Omoigui et al. (2006) used full-sib family selection to develop maize cultivars tolerant to low N under selection conditions of low and high N. They obtained genetic gains in GY of 2.3% and 1.9% cycle^{-1}, under low and high N, respectively. They also recorded an increase in stay green by 17% and 4.7% cycle^{-1} under low and high N, respectively. This suggests that mechanisms conditioning GY under low N, differed from those under high N conditions and that performance under low N was not at the expense of performance under high N. In this study, S_1 selection was used to identify genotypes that achieved high yield under low N (tolerated the stress).

1.6.3 Selection for tolerance to drought

Although drought that occurs at post emergence, when genotypes could be discriminated from one another based on Lroll, drought was most serious at flowering, when farmers are unable to replant and this type of drought needs a genetic solution (Zambezi and Mwambula, 1997; Banziger et al., 2000). In breeding for tolerance to drought, care should be taken to ensure that the stress is uniformly applied to the genotypes. Data from different fields that depended on rainfall may not be appropriate, as the drought may occur at different stages of growth. Managed drought with irrigation offers a solution to this.

Bolanos and Edmeades (1993) used recurrent selection, under managed drought at flowering (using furrows irrigation) and increased GY by 108kg ha^{-1} cycle^{-1}. This was mainly as a result of an increase in EPP of about 0.03 cycle^{-1} under drought conditions. Therefore, managed drought at flowering could be an effective selection environment for increasing GY under drought conditions. Grain yield increase under drought stress was associated with a reduction in ASI and barrenness (Zambezi and Mwambula, 1997). Byrne et al. (1995) reported a GY increase of 1.68% cycle^{-1} under managed drought and attributed the increase to selection for reduced ASI under drought conditions. Beck et al. (1997) found that selection for drought tolerance in local 'adapted' populations accelerated breeding progress for GY. Yitbarek (1997) used S_1 recurrent selection to develop a drought tolerant synthetic variety that yielded above 3t ha^{-1} under drought conditions in Ethiopia, by recombining the best 5-15% of the S_1 families. In this study, S_1 selection was used in identifying maize genotypes that tolerated drought.

1.7 Grain yield stability

Farmers cultivate maize under contrasting environmental conditions and GY stability of a variety is important if it is to attract wide adoption. Grain yield stability (repeatability in performance) may be static when GY of a variety remains unchanged regardless of environmental conditions, or dynamic, when GY of a genotype changes in a predictable manner across a wide range of environmental conditions (Tollenaar and Lee, 2002). This section reviews the estimation of stability, using information on genotype x environment interaction effects and relative yield reduction of a genotype under optimal and stress (low N or drought) conditions.

1.7.1 Genotype x environment (GE) interaction effects

Plant growth and development is a result of the interplay between the genetic potential of the plant and the environment (Quizenberry, 1982). Differential genotypic expression across environments is known as genotype x environment (GE) interaction effects (Fox et al., 1997). The existence of GE may mean that the best genotype under one level of stress caused by low N or drought is not the best genotype in another level of stress (Falconer, 1981). When GE interaction effects are non-significant, varietal means across environments are adequate indicators of genotypic performance across the environments. In this situation, the varieties are said to be stable across the environments. However, when GE is significant, subsets of environments are often masked where genotypes differ markedly in relative performance. Significant GE means that selections from one environment may often perform poorly in another and the variety is not stable across the environments. Therefore, information on GE may help in determining a breeding strategy such as whether to aim for specific or wide adaptation. When there are changes in rankings of genotypes across environments, the type of GE is called crossover type interaction effects (Fox et al., 1997). This implies that genotypes show specific adaptation to defined environments. Where non-crossover type of interaction effects exists, genotypes with superior means can be recommended for all the environments (Romagosa and Fox, 1993). Information of GE may also be useful for a breeder to choose locations for selection (Fox et al., 1997).

Sallah et al. (1997) found significant GE interaction effects for GY, days to mid silking, plant height, and EPP, under both high and low N, implying that the fertility level influenced genotypic expression. This requires re-determination of appropriate N fertility rates for the area. Gallais and Coque (2005) observed that many studies showed significant genotype x N interaction effects for GY. They attributed this to genotype x N interaction effects for kernel number, and concluded that reducing kernel abortion, just after fertilisation, increased tolerance to low N. Significant genotype x N interaction effects for GY means N differentially influences GY achieved by genotypes. Therefore, efficiency of selecting superior genotypes for both high and low N environments is low.

Dass et al. (1997) proposed that in selection for drought tolerance, genotypes which were less sensitive to genotype x environment interaction effects should be utilized. They reported that this enabled the development of genotypes not only stable across different levels of drought but also good combiners for further improvement. As drought stress levels often differ from field to field and within the same field, mainly due to soil type variation, use of less GE sensitive germplasm offers an effective breeding strategy for improving mean yields at the farm level.

Much of the maize breeding targeting the tropics is conducted under well-fertilised and well-watered conditions yet upon release, socio-economic circumstances in Zambia often dictate that farmers grow these varieties under low input crop management practices. This implies that the variety is selected indirectly for the farmer environment. Where GE is important, such genotypes may fail to perform. Use of a selection environment that differs considerably from the target environment (indirect selection), is predicted to be more effective than direct selection in the target environment itself when:

$$h_T < |r_G h_S|$$

where h_T and h_S are the square roots of the heritabilities of GY in the target and selection environments and r_G is the genetic correlation between grain yields in both environments (Falconer, 1981; Banziger et al., 1997). Experiments to test this theory have in general confirmed findings that direct selection is superior to indirect selection because it is rare to find $h_T < |r_G h_S|$ (Falconer, 1981). Therefore, breeders should select in environments that best represent the farmer situation while not ignoring high yielding environments.

1.7.2 Relative grain yield reduction

Most plant breeding is based on selection for yield. Jugenheimer (1976) reported that maize yield of about 20t ha^{-1} was obtained under optimal conditions in temperate environments, while only about 1-2t ha^{-1} were common under marginal environments in the tropics. Within the tropics, genotypes that yield over 10t ha^{-1} at research stations, often yield only 1t ha^{-1} under small-scale farmer cultivation (Zambezi and Mwambula, 1997). Stability for GY of a variety is important because farmers cultivate the same variety under different management systems. Tollenaar and Lee (2002) found that much of the yield increase of maize in the United States of America was due to enhanced stress tolerance. Drought and low N cause different levels of stresses to plants in an area because many other factors (e.g. soil type) also affect them. It is, therefore, important that yield stability is developed in cultivars targeting such environments.

Reduction of GY of a genotype under abiotic stress, when compared to its performance under recommended crop husbandry, could indicate its level of stability in performance under the two different environments. A smaller yield reduction under stress indicates stability of the genotype and suggests wide adaptation. Rosielle and Hamblin (1981) defined low yield reduction as tolerance to stress. Given y_1 = grain yield under optimal (non stress) and y_2 = grain yield under stress (low N or drought), tolerance was defined as $y_3 = y_2 - y_1$. This represents the ability to limit yield reduction between the two environments and maintain static stability. The weakness of this measure is that y_3 is small when both y_2 and y_1 are small i.e. it is a low yielding variety in all experiments. Farmers rank varieties differently when grown under different crop environments (Banziger and Cooper, 2001; Banziger and de Meyer, 2002). This implies that the varieties lack static stability and performed differently under different environments.

1.8 Molecular approaches in breeding for low N and drought tolerance

Although low N and drought are the most constraining factors to maize production in Zambia, the country lacks varieties that adequately tolerate the stresses. Low GY heritability under the stresses and low correlation between GY and secondary traits limits accurate selection of genotypes that tolerate the abiotic stresses (Banziger and Cooper, 2001). This has led to slow progress in breeding for tolerance to abiotic stresses. Marker Assisted Selection (MAS) could be a probable solution to this. Molecular markers could be used to identify genotypes of interest, which could be used for crop improvement. Superior genotypes could be identified at seedling stage using MAS, and depending on a breeding strategy, a breeder would be able to cross the desired genotypes within a season when no stress was present. Therefore, MAS could strengthen a breeding programme in both precision and speed of progress. However, this requires use of precise markers. Ribaut et al. (2007) identified eight quantitative trait loci (QTL) for GY under low N. Of these, two were also detected under high N which could be used in laboratories to identify genotypes that tolerate low N stress and also have high yield under optimal conditions. Cattivelli et al. (2008) reported that maize hybrids which were selected with molecular markers for four generations yielded about 50% more than control hybrids under severe drought. This implies that MAS could accelerate development of varieties tolerant to abiotic stresses. However, there are no MAS facilities in Zambia, and crop improvement depends solely on conventional breeding.

1.9 Adoption of improved maize varieties

The ultimate objective of every breeder is that the developed variety reaches farmers. In Zambia, prior to its release, a maize variety is tested for distinctness, uniformity and stability (DUS) as well as for value for cultivation and use (VCU) in all the three agro-ecologies of Zambia during the rainy season (Mungoma et al., 1997). In managing field trials, recommended crop husbandry practices are followed including fertilisation to ensure that plants under evaluation are less stressed. This means that candidate varieties are not assessed for tolerance to stresses such as drought or low N, prevalent under small-scale farmer cultivation. It assumes that farmers would control the stresses during crop cultivation. However, upon release such varieties fail in farmers' fields and are largely not adopted. From about 155 maize varieties released in the country (SCCI, 2007), only about a third were multiplied (Silwimba and Miti, 2005). Consequently, 68% of agricultural households planted local unimproved varieties of maize (CSO, 2005). The majority of farmers using local unimproved varieties were small-scale (Phiri, 2004) accounted for 92% of Zambia's farming community (MAFF, 1999) and were the main producers of maize in the country (CSS, 2001).

Kumar (1994) reported that farmers in Eastern Zambia grew local maize for their own consumption and sold any hybrid maize produced. This probably suggests that further commercialization of maize production among small-scale farmers could increase use of seed of improved varieties of maize. Use for consumption of local maize suggests its superiority in taste, processing and storage. Even though farmers know that there is a yield advantage by growing hybrids, some characteristics in the local maize varieties attract them to continue growing them. Use of local unimproved varieties is concentrated among resource poor and small-scale farmers, suggesting that the farmers cannot afford additional inputs such as irrigation and fertilisers or cannot afford to take risks, in addition to the lack of their specific preferences in the improved varieties. Maize grain price is about US$0.2 per kg and is six and nine times the price of a kg of nitrogen and seed, respectively. Bellon et al. (2005) observed that landraces used by small-scale farmers in Mexico reflected their values and preferences. Breeders need to understand the farming condition of small-scale farmers in order to develop appropriate varieties for their environment.

Provision of improved varieties that respond to high inputs as the ideal farming model may not be appropriate for small-scale farmers (Banziger and Diallo, 2004). It assumes that small-scale farmers can also become successful commercial farmers by adopting this model. Unfortunately, this is difficult to achieve, as it depends on a series of conditions being present at the same time: optimal soil fertility, optimal soil moisture, adequate finance, sound cash flow, high levels of management, assured markets and guaranteed prices. These conditions are mostly deficient in the smallholder sector. As a consequence of the promotion of inappropriate high input technologies, yields of the staple food crop in the country, maize, are declining steadily and household food security is deteriorating (Siacinji-Musiwa, 1999**)**. One of the undesirable consequences of this misdirection is that many small-scale farmers use their meagre resources to purchase as much of a high input package as possible, while other important conditions fall far short of what is required to achieve optimal yields such as infrastructure and roads. Thus, scarce resources are used much less effectively than they could be; in the face of diminished returns, scarce resources become even scarcer.

Most small-scale farmers have probably found improved maize varieties not suitable for their crop growing conditions and preference. Understanding of genetic gains in farmer selection, under sub-optimal crop conditions, may strengthen strategies for developing varieties not only for the stress environments; but also with farmer preferred characteristics that will increase their adoption by farmers. According to the World Bank (2004), farmers' needs may be classified according to the crops grown by them, their resource endowments and risk-tolerance capacities. An effective seed system comprising plant breeding, marketing and the use of seed crops must have a strategy for each category of farmers.

Langyintuo et al. (2003) highlighted three main paradigms explaining technology adoption decisions by farmers. They are the innovation-diffusion model, the economic constraint model and the adopter’s perception explanation. The innovation-diffusion model describes the situation where the technology is appropriate and the problem of technology adoption is one of lack of information. The model contends that if farmers get the information, they will adopt the new technology. In Zambia information about improved varieties has been disseminated to farmers primarily through the extension service of the Ministry of Agriculture and Cooperatives, MACO (formally Ministry of

Agriculture, Food and Fisheries, MAFF). Seed promotions including field days, on-farm trials, strategic demonstration plots, farmer training, farmer agriculture shows, print and electronic media have been carried out country-wide to popularize use of improved varieties. However, most small-scale farmers have not been keen in investing in improved maize seed varieties.

The economic constraint model provides that farmers are constrained to access credit, land, labour and other critical inputs, limiting production flexibility and conditioning technology adoption decisions (Langyintuo et al., 2003). It implies that farmers would adopt the new technologies when the economic constraint is removed. This constraint arises due to the failure to adopt when information is available in the farmer perception model. Entirely solving economic constraints of small-scale farmers is a nightmare in a country like Zambia that has a poverty level of about 68% (CS0, 2005) and therefore with huge economic demands. However, an effective government policy on strengthening input provision to small-scale farmers could be an effective strategy to enhance adoption of new varieties and increase agricultural production.

The farmer's perception of a new technology is important, if it is to be adopted. The technology may be appropriate, but subjective perceptions may limit the adoption process. Obtaining farmer perception on the appropriateness of characteristics of a technology under investigation can strengthen the focus of the research and direct appropriate technology development strategies. Through the extension service, plant breeders in Zambia obtain information on farmer perceptions on various characteristics limiting maize production. Feedback information on farmer perception of released varieties is also obtained through the same channel. It is also obtained from results of surveys by, among others, the Central Statistical Office (CSO). Farmers perceive improved varieties as expensive and, lacked storability, palatability and tolerance to abiotic stresses. Most of the varieties developed require a farmer to change an existing practice of crop production, such as demand for fertiliser application. Small-scale farmers have found it difficult to adjust and meet the demands of new improved varieties. Development of new varieties should probably also focus on performance under existing farming practices of small-scale farmers.

1.10 Summary

The review of the literature has established that drought and low N limit maize production of the majority of resource poor small-scale farmers in Zambia. However, research on breeding maize for tolerance to drought or low N is scarce. This could imply that varietal development is generally not serving small-scale farmers well, but is serving those who can afford additional inputs. This explains why maize yields by small-scale farmers continue to be only about 1.79t ha^{-1} (CS0, 2006b).

It has been found that the potential yield for maize varieties in Zambia was over 5 times that obtained by small-scale farmers. The gap from potential to actual maize yields obtained by small-scale farmers has contributed to low adoption of the improved maize varieties in the country. It offers a challenge for plant breeders in Zambia to develop varieties targeting the resource poor small-scale farmers. Use of secondary traits of high heritability and correlation with GY could strengthen selection of superior genotypes and accelerate breeding progress. More research is also required in this area to contribute to increasing maize yields.

Literature on developing maize varieties that tolerate drought or low N is recent, suggesting that the area under review is only beginning to receive attention. Although work on breeding for the same is limited, recently there has been some research on the two traits. The same will be useful in understanding the genetics of maize plants in developing varieties for drought or low N crop environments.

It is generally agreed that additive gene action conditions GY under drought but reported gene action that conditions the same under low N varies. Knowledge of gene action important for secondary traits under low N and drought is limited. More information on type of gene action conditioning GY and secondary traits under the abiotic stress is required to improve breeding strategies targeting low N and drought environments.

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Chapter 2: Farmer preferences in selecting maize crop cultivars in three agro-ecological regions of Zambia and implications for plant breeding

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Abstract

Despite the release of 155 maize cultivars in the country, most farmers in Zambia depend on local unimproved cultivars (landraces) for planting. A study was conducted to identify small-scale farmer preferences that influenced adoption of improved maize cultivars in Zambia. Both formal and informal surveys were conducted in Luangwa, Chibombo and Lufwanyama rural districts representing the three agro-ecological regions in Zambia, during the 2004/05 agricultural season. Participatory Rural Appraisal (PRA) tools such as focus group discussions and personal interviews were used to collect data on issues that affected maize production in these areas. It was found that food security, need to apply fertiliser and drought tolerance had significant ($p \leq 0.05$) influences in causing farmers to adopt improved maize cultivars. Therefore, poor grain yields under small-scale farmer crop environments characterized by drought and low soil fertility de-motivated farmers into planting improved varieties. Farmers depend on landraces, although these too are low yielding. To improve their landraces, most farmers selected seeds based on flintiness, grain and cob sizes. Although farmers perceived the landraces to be low yielding, they believed that they are superior to improved cultivars for: resistance to pests and diseases (65.8%); tolerance to drought (30.8%); tolerance to low soil fertility (40.8%); grain palatability (82.5%); grain storability (91.7%); and poundability (88.3%). Therefore, in developing drought and low soil fertility tolerant cultivars, inclusion of local landraces with adaptability to these conditions is advised. Additional characteristics should include farmer preferred traits such as flintiness, grain and cob sizes, poundability, palatability and storability.

Key words: Maize, PRA, preference, adoption, abiotic stress

2.1 Introduction

Although Zambia has many improved maize cultivars, most small-scale farmers, who account for over 90% of the farming community plant local unimproved cultivars (MAFF, 1999; CSS, 2001). Seed Control and Certification Institute (SCCI, 2007) reported that 155 maize cultivars have been released for commercial production in Zambia, but only about a third of these were multiplied (Silwimba and Miti, 2005). The Central Statistics Office (CSO, 2005) found that about 68% of Zambian agricultural households planted maize using landraces and yields are low. Average maize yield among the small and medium scale farmers in Zambia using either local or improved cultivars, was 1.79t ha^{-1} and ranged from 0.58t ha^{-1} to 3.10t ha^{-1} (CSO, 2006). The low yield in this staple food crop contributes to a high level of poverty, estimated to be 79% among small-scale farmers (CSO, 2005).

There are arguments that small-scale farmers use landraces because improved seed cultivars are not available in rural areas (FAO and ADB, 2004) where the farmers are located due to poor infrastructure that limits seed delivery to farmers**.** However, seven major seed companies, among them internationals, are involved in the provision of maize seed in Zambia. They include; Zambia Seed Company, Maize Research Institute, SeedCo International, Pannar, Kamano, Monsanto and Pioneer, suggesting that there is adequate interest in seed supply to the country. Some studies have revealed that most small-scale farmers in rural areas cannot afford improved seed cultivars because they lack financial resources (Zambezi and Mwambula, 1997). However, they are able to purchase other items such as food, clothes, shoes, alcohol and groceries (Balat and Porto, 2005). This suggests that farmers are not keen to spend on seeds.

It may be argued that farmers do not get the full benefit of using improved maize cultivars, hence their continued dependence on landraces. According to Zambezi and Mwambula (1997) improved cultivars yield as low as 1t ha^{-1} on farmer fields compared with over 10t ha^{-1} at research stations. This wide gap reflects the difficulties farmers face in cultivating maize. Addressing the reasons for such a huge difference would contribute greatly to enhancing maize production in Zambia. In a study to evaluate maize landraces that could be used as germplasm to enhance forage yield and quality, Bertoia et al. (2006) found that some landraces were superior to commercial hybrids in whole plant yield i.e. total biomass. Some Zambian landraces probably yield more grain or exhibit characteristics more preferred by farmers than improved cultivars when grown under farmer conditions, hence, their general preference for them. Information on performance of maize landraces in comparison to improved cultivars in Zambia's farming systems could contribute not only to understanding the low adoption of improved cultivars, but also strengthening the focus of cultivar development.

Maize is an open pollinated crop and new genetic combinations are continuously being formed in farmer fields through natural out crossing. Farmers in many parts of the world understand that the genetic composition of their cultivars changes with every cropping cycle and, in selecting seed for planting, they choose those that exhibit desirable traits (Morris, 2002). This could have led to development of landraces suitable to their local environment. Breeders can only identify such germplasm by working with farmers. Understanding farmer preferred characteristics is, therefore, important in order to develop appropriate cultivars which address farmer preferences and to increase their chances of being adopted by farmers.

The ultimate aim of a breeder is to develop a cultivar that will be used by farmers. According to Morris (2002), farm level decision to adopt a maize cultivar is influenced by a complex and highly variable set of factors. These include demographic characteristics of the household, expected profitability of the technology, farmer consumption preferences and availability and cost of seeds. Langyintuo et al. (2003) highlighted three main paradigms explaining technology adoption decisions by farmers, namely the innovation-diffusion model, the economic constraint model and the adopter's perception explanation. The innovation-diffusion model argues that the technology is appropriate but the problem of technology adoption is one of inadequate information. The model shows that if farmers understand the information, they will adopt the new technology.

Farmer perception of a new technology is important if it is to be adopted. The technology may be appropriate, but subjective perceptions may limit the adoption process. Obtaining farmer perceptions on the appropriateness of characteristics of a technology under investigation can strengthen the focus of plant breeding and direct appropriate technology development strategies. Binns et al*.* (1997) reported that top-down rural development strategies in Africa have generally not succeeded in raising living standards among the rural poor. They argued that inappropriate development strategies have stemmed from methodologies that fail to appreciate the whole picture in rural communities, and in particular ignore local people's perceptions, needs and understanding. Obtaining farmer perception on the appropriateness of a breeding objective can strengthen the focus of the research and direct appropriate technology development strategies.

The economic constraint model (Langyintuo et al*.,* 2003) suggests that farmers are constrained by access to credit, land, labour and other critical inputs, limiting production flexibility and conditioning technology adoption decisions. It implies that farmers would adopt the new technologies if economic constraints were removed.

In this study, farmer preferences for maize cultivars were assessed in three rural districts of Zambia. The findings of this work are incorporated into the maize cultivar development strategy. The hypothesis tested in this study is that there is low adoption of improved maize cultivars because the technology fails to meet farmer requirements.

2.2 Materials and methods

A Participatory Rural Appraisal (PRA) and a formal survey were carried out in Luangwa, Chibombo and Lufwanyama rural districts of Zambia to assess farmer preferences in selecting maize cultivars. The three districts purposively sampled from agro-ecological Regions I, II and III, respectively, are outlying and the local populations depend on agriculture for their livelihoods. Region I lies in the low lands and receives rainfall of up to 800mm per annum, over 80-120d, with about five 10d dry periods receiving less than 30mm per period in an average season. Region II annually receives between 800-

1000mm, over about 100-140d, with about three 10d dry periods of less than 30mm per period/year. Region III receives over 1000mm of rainfall, over 120-150d in a year with a probability of 70% (Bunyolo et al., 1997) and does not experience drought. Soils in Luangwa are more fertile than those at Chibombo which are superior in fertility to those at Lufwanyama (Bunyolo et al., 1997).

In each district, two agricultural camps and two villages per camp were selected for the PRA. In order to provide advisory service to all farmers in the country, the Ministry of Agriculture and Cooperatives (MACO) divided the country into camps. On average a district may contain about 6 camps and at least 30 villages camp^{-1}, 10 households village^{-1} and seven members household^{-1}. Participation in the PRA was restricted to males and females over 15 years old. At least 30% of the sample was female farmers. The check list used in the PRA covered broad issues on farmer crop environment and general farmer perception. The issues covered livelihood strategies and food security, farming system, access to market, cultivar analysis, production constraints and cultivar selection criteria. In each village a group of 10 farmers debated issues raised from the check list in a questionnaire (appendix 2.1) and collectively responded to them i.e. one questionnaire for all 10 farmers.

In order to obtain detailed information on specific issues covered under the PRA, a formal survey followed in which 120 individual farmers, drawn from similar areas selected for the PRA (40 per district), were interviewed using a semi-structured questionnaire. Of these about 53% were male farmers. The questionnaire (Appendix 2.2) covered: (1) farmer specific characteristics such as age, education, gender, size of family, farming experience, family labour availability, membership to an association, extension contact and infrastructure; (2) farm specific characteristics such as size of the farm, land tenure status, access to credit, distance of farm to input and grain markets; and (3) technology specific attributes such as cultivar, yield, prolificacy, pest resistance, disease resistance, taste, poundability (milling), storage, tolerance to biotic and abiotic stresses. The survey also investigated small-scale farmer perceptions on released cultivars with respect to type, suitability for small-scale farmers, speed of cultivar release, seed delivery, suitability to different soils and drought. Characteristics preferred by farmers in selecting seed from their local maize were also sought.

Using the same villages selected for the PRA, 10 farmers per village were selected from each village, using quota sampling, to ensure the participation of both male and female farmers. Where the selected individual was unable to participate in the survey, a replacement was randomly selected. Questionnaires were administered by trained technicians drawn from the Extension Branch of the Ministry of Agriculture and Cooperatives (MACO) in the respective districts. In addition to the PRA and the formal farmer survey, 50 key stakeholders within 100km of Lusaka were purposively selected and interviewed using a questionnaire (Appendix 2.3) designed to capture information on the protocols for maize breeding and release in Zambia. They included five representatives from public breeders, private breeders, seed production, Variety Release Committee, seed marketing, commercial farmers, the seed certification authority, extension service, seed associations and NGOs involved in agriculture. Information solicited included livelihood strategies of people in rural areas, seed delivery, produce market, and variety release with respect to speed, type, suitability for small-scale farmers, suitability for different soils and tolerance to drought. Data collected were coded and analyzed using STATA (StataCorp, 2004). Means and coefficiencies of pairwise correlation and Tobit regression were computed. Both a combined analysis and site (district) specific analysis of data were. Where a characteristic was significant in a combined analysis, specific district results were reported.

2.3 Results

2.3.1 Demographic characterization of households

Results from the formal survey indicated that sex of the household head (hh) was not significantly different ($p \leq 0.05$) among the three districts, nor were hh that were widowed or divorced. Number of hh that never went to school, attended tertiary education or belonged to an association did not differ among districts, nor was number of family labour units. However, age of hh was significantly different and so were married and single households across the districts. Number of household heads that attended primary and secondary education was significantly different, and so was regular contact with the extension services.

The majority of farmers interviewed across the three districts were married and the modal age group was between 35 and 65 years (Luangwa and Chibomba) and 16 – 35 years in Lufwanyama. At least 80% of the household heads in the districts had lived in a village for more than 10 years practicing small-scale farming and had acquired experience in farming in their villages.

The majority of households were male headed (76.7%) and only 23.3% female headed (Table 2.1). The majority of hh across districts attended primary school education while only 12.5% (Luangwa), 25% (Chibombo) and 27.5% (Lufwanyama) attended secondary education. Only 0.8% attended post secondary education while 8.3% had never been to school across the three districts.

Regular contact with extension service was 72.5% (Luangwa), 47.5% (Chibombo) and 75% (Lufwanyama), across districts while 45% belonged to an association. Those who were not members of any association were either not aware of its existence (54%) or were unclear of benefits of belonging to such groups (46%). About 46% of the households had more than five members.

Age of the household head (16 – 35 years) significantly ($p \leq 0.05$) correlated negatively (r) with belonging to an association (r = -0.245*) and regular contact with extension (r = -0.199*) but positively among small households (r = 0.306*) of less than five members (Table 2.2).

Table 2.1: Demographic characterization of households (%)

	District			
Variable	Luangwa	Chibombo	Lufwanyama	Average
1. Sex of household head				
a) Female headed	27.5	22.5	20.0	23.3
b) Male headed	72.5	77.5	80.0	76.7
2. Age of household head (yr)				
a) 16.00 – 35.00	32.5	30.0	55.0	39.2*
b) 35.01 – 65.00	65.0	50.0	45.0	53.3*
c) Above 65.00	2.5	20.0	0.0	7.5*
3. Marital status				
a) Married	82.5	65.0	82.0	76.5*
b) Single	12.5	22.5	15.0	16.7*
c) Widowed	2.5	7.5	1.5	3.8
d) Divorced	2.5	5.0	1.5	3.0
4. Over 10 years experience in farming	90.0	80.0	97.5	89.2
5. Above 5 family labour	52.5	50.0	35.0	45.8
6. Level of education acquired by household head				
a) None	7.5	12.5	5.0	8.3
b) Primary school	80.0	60.0	67.5	69.2*
c) Secondary school	12.5	25.0	27.5	21.7*
d) Tertiary education	0.0	2.5	0.0	0.8
7. Household heads belonging to an association	42.5	42.5	50.0	45.0
8. Household heads having regular contact with extension	72.5	47.5	75.0	65.0*

* denotes significantly differently from each other within the same class at $p \leq 0.05$

Female headed households correlated positively with no education (r = 0.190*). Households that had enough food through to the following harvest were described as food secure. Family size of more than 10 members correlated positively with food security (r = 0.186*) and high maize yield (r = 0.300*). There was also significant correlation between food security and contact with extension (r = 0.205*) and with being a member of a farmer association (r = 0.212*). However, farming experience correlated (r = 0.346*) with an increasing weed problem.

Table 2.2: Pair wise correlations of some farmer characteristics with grain yield (GY) and food security

	GY $t\ ha^{-1}$			Age of household head (hh)				Education		Size of household			
	High (>4)	Low (<1)	Female hh	16-35 yrs	> 65 yrs	>10 years Farming	Member of assoc.	None	Tertiary	< 5	> 10	Contacts extension	Food secured
High GY (>4$t\ ha^{-1}$)	1												
Low GY (<1$t\ ha^{-1}$)	-0.295*	1											
Female hh	0.007	0.128	1										
Age of hh 16-35	-0.149	0.050	0.042	1									
Age of hh >65	-0.053	-0.172	0.067	-0.229*	1								
Farming for >10 years	0.065	-0.100	0.129	0.005	0.099	1							
Member of association	0.112	0.011	0.055	-0.245*	-0.003	0.046	1						
No education	0.112	-0.078	0.190*	-0.118	0.143	-0.089	0.030	1					
Tertiary education	-0.017	-0.146	-0.051	-0.074	0.322*	0.032	-0.083	-0.028	1				
Household <5	-0.106	0.079	0.082	0.306*	-0.051	-0.004	-0.060	0.040	0.086	1			
Household >10	0.300*	-0.242*	0.067	-0.164	0.039	0.099	0.188*	0.029	-0.026	-0.304	1		
Contacts extension	0.136	-0.074	0.033	-0.199*	0.010	0.194*	0.488*	0.032	0.067	-0.021	0.076	1	
Food secured	0.098	-0.332*	0.024	-0.059	0.114	0.089	0.212*	-0.046	0.152	0.073	0.186*	0.205*	1

* denotes data significant at $P \leq 0.05$

2.3.2 Access to resources

Farm size, distance to market, participation at field days, food security, and access to credit and tractor services were all significantly different (p ≤ 0.05) across the districts. However, type of seed planted was marginally significant (p = 0.05) while access to land and fertiliser were not significant (Table 2.3). All farmers interviewed in Luangwa lived far away (> 50km) from a reliable source of agricultural inputs and faced difficulties in accessing the markets. Most farmers lived within 20km to input market in Chibombo and Lufwanyama. The majority of farmers interviewed (96.7%) reported to have had no difficulties in accessing farm land, although most of the farmers in Luangwa (95%) and Lufwanyama (70%) cultivated only up to 2ha while the majority in Chibombo (57%) cultivated 2-5ha. In contrast, access to credit was only 7.5% (Luangwa), zero (Chibombo) and 32.5% (Lufwanyama).

Table 2.3: Households access (%) to farmland and services in the study districts

Variable	Luangwa	Chibombo	Lufwanyama	Average
1. Access to land for farming (%)	100.0	95.0	95.0	96.7
2. Farm size (ha)				
a) 0.01-2.00	95.0	22.5	70.0	62.5*
b) 2.01-5.00	5.0	57.5	27.5	30.0*
c) More than 5	0.0	25.0	2.5	9.2*
3. Distance to input market (km)				
a) 0.01-5.00	0.0	45.0	25.0	23.3*
b) 5.01-20.00	0.0	20.0	25.0	15.0*
c) 20.01-50.00	0.0	0.0	12.5	4.2*
d) Above 50	100.0	35.0	37.5	57.5*
4. Household food secured (%)	17.5	27.5	35.0	26.7*
5. Access to credit facilities (%)	7.5	0.0	32.5	13.0*
6. Access to improved seed (%)	12.5	30.0	25.0	22.5*
7. Did not apply fertiliser (%) – basal	60.0	65.0	55.0	60.0
8. Did not apply fertiliser (%) – top	60.0	52.5	50.0	54.2
9. Did not irrigate maize (%)	0.0	0.0	0.0	0.0
10. Access to tractor (%)	0.0	7.5	2.5	3.3*
11. Participate in field days (%)	47.5	70.0	50.0	55.8*

* denotes that the districts differed significantly at p ≤ 0.05

Much of the seed accessed by farmers were landraces obtained from within their local communities. The seeds were those saved from a previous harvest and farmers accessed the same through their own savings (69%), gift (9%) or sales (22%).

Lack of access to credit significantly ($p \leq 0.05$) correlated ($r = -0.265^*$) with use of improved seeds, but correlated positively ($r = 0.290^*$) with use of local cultivars (Table 2.4). High yields correlated positively ($r = 0.263^*$) with large fields (> 5ha). Cultivating large fields was also positively corrected with proximity to inputs ($r = 0.303^*$). Food security was negatively correlated with lack of credit ($r = -0.306^*$) and use of unimproved local cultivars ($r = -0.603^*$) while it correlated positively with use of improved cultivars ($r = 578^*$).

Table 2.4: Pair wise correlations of some farm specific characteristics with grain yield and food security

	Grain yield (GY)		Farm size		Distance to input			Access to credit		Type of seed cultivar	
	High	Low	< 2ha	> 5ha	Near (<5km)	Far (>50km)	Food secured	Good	None	Improved	Local seed (landrace)
High GY (>4t ha^{-1})	1										
Low GY (<1t ha^{-1})	-0.295*	1									
Farm <2ha	-0.144	0.201*	1								
Farm >5ha	0.263*	-0.185*	-0.410*	1							
Near to input	0.007	-0.047	-0.468*	0.303*	1						
Far to input	0.066	0.095	0.379*	-0.136	-0.642*	1					
Food secured	0.098	-0.332*	-0.156	0.136	-0.065	0.175*	1				
Access credit	0.064	-0.134	-0.101	-0.040	0.131	-0.109	0.152	1			
No access to credit	-0.168	0.235*	-0.023	-0.026	0.046	-0.093	-0.306*	-0.565*	1		
Improved seed	0.122	-0.281*	-0.118	0.106	0.033	0.100	0.578*	0.082	-0.265*	1	
Local landrace seed	-0.117	0.265*	0.102	-0.098	-0.022	-0.116	-0.603*	-0.131	0.290*	-0.977*	1

* denotes data significant at $P \leq 0.05$

2.3.3 Crop production

The livelihood strategy of the majority of households (99.2%) was crop production with maize as the dominant crop for all the farmers interviewed (Table 2.5). This was in agreement with about 98% of the stakeholders interviewed. However, there was variation among farmers on the second most important crop. On average groundnuts followed maize, while cash crops (cotton, soybeans) were third and were followed by cassava (Fig. 2.1). Other crops included sweet potato, sorghum, millets, beans and paprika.

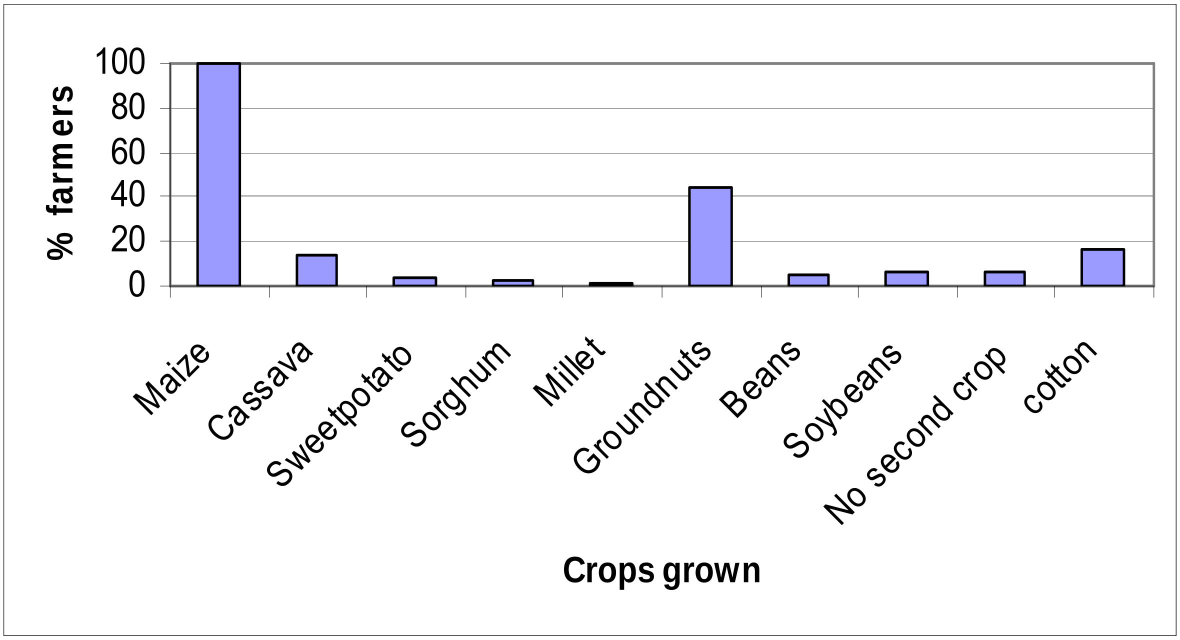

Fig. 2.1: Crops grown by farmers in study areas

Farmers interviewed had adequate land for crop production and allocated much of it to maize. Despite the fact that farmers cultivated a number of crops it was a general consensus that farm incomes per household were too low to meet household needs. The farmers usually failed to purchase agricultural inputs (seed, fertilisers and irrigation) and obtained low yields.

All the farmers were aware of the existence of improved maize cultivars and that they would have high yields high when recommended crop management practices were followed. However, the majority of farmers interviewed planted landraces (Fig. 2.2.)

while only 22% planted improved seeds. The most critical problem in cultivation of maize was lack of seed source (Luangwa), failure to purchase seed (Chibombo) and failure to buy fertiliser (Lufwanyama). Grain yields were < 1t ha^{-1} for a majority of farmers in Luangwa (87.5%), Chibombo (67.5) and Lufwanyama (60.0%).

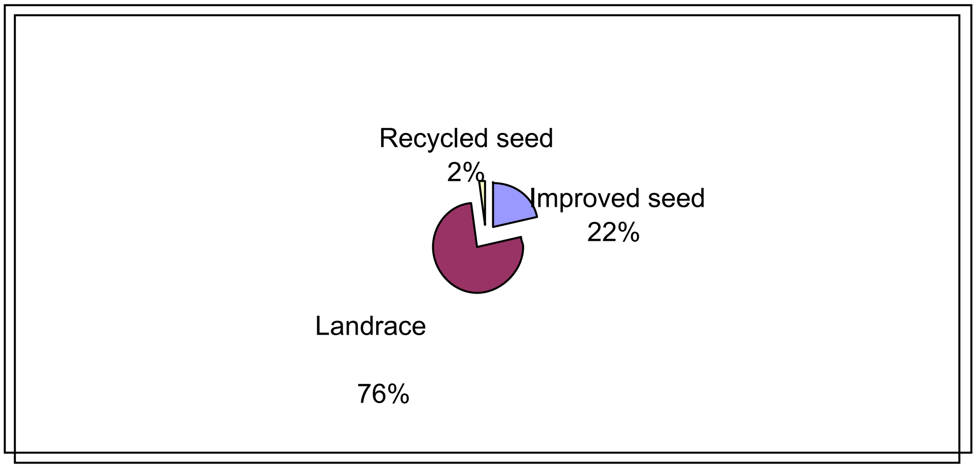

Fig. 2.2: Types of seed planted by farmers in the study areas

About 46% of the stakeholders interviewed thought farmers did not prefer improved maize seed. They felt that farmers did not want to spend on seed because they had an alternative in the landraces. Landraces were also less expensive and were readily available through savings from previous harvest. Much of the landrace seed was farmer saved (67%) while twenty-two percent was procured from within local community and about 11% accessed it through gifts. About 68% of the farmers who planted improved seeds accessed them through relief programmes by government and/or non-governmental organizations (NGOs) while only 20% accessed the seeds through private traders and the rest (12%) through relatives and friends.

Table 2.5: Crop production by farmers (%)

	Districts			
	Luangwa	Chibombo	Lufwanyama	Average
1. Crop production as a livelihood strategy (%)	100.0	100.0	97.5	99.2
2. Maize the main crop (%)	100.0	100.0	100.0	100.0
3. Land preparation (%)				
a) Tractor	0.0	7.5	2.5	3.3*
b) Ox-drawn plough	0.0	65.0	37.5	34.2*
c) Hoe	100.0	25.0	60.0	61.7*
4. Planting of maize (%)				
a) Always on time	35.0	57.5	30.0	40.8*
b) Sometimes on time	52.5	10.0	45.0	35.8*
c) Always late	12.5	32.5	25.0	23.4*
5. Seed planted by farmers (%)				
a) Improved maize seed	12.5	30.0	25.0	22.0*
b) Local unimproved seeds	85.0	70.0	75.0	76.0*
c) Recycled seeds	7.5	0.0	0.0	2.0*
6. Maize yields obtained by farmers (t ha^{-1})				
a) Maize yield of above 4	0.0	7.5	2.5	3.3*
c) Maize yield of 1-4	12.5	25.0	37.5	25.0*
d) Maize yield < 1	87.5	67.5	60.0	71.7*

* denotes significant at $p \leq 0.05$

The PRA conducted during the study also found that the use of landraces for planting was common among farmers and only a few planted improved cultivars of maize. Farmers claimed that seeds of improved cultivars were either not locally available or available but too expensive to access. They noted that seeds of improved maize cultivars yielded higher than their landraces when fertilisers were applied and lamented that provision of relief seed maize by government or non-governmental organizations (NGOs) without fertiliser did very little to improve yields. Without fertiliser, farmers preferred landraces thought to perform better than the improved ones under low soil fertility and drought conditions. Additionally, local cultivars were known to store and taste better than improved cultivars.

The study established that much of the land preparation was by hand hoeing in Luangwa (100%) and Lufwanyama (60%) while it was by ox-drawn plough in Chibombo (65%). Preparation of land was generally done early enough in time to plant with the first rains. However, earliness in planting was found to vary considerably among the farmers in the three districts (Table 2.5). About 41% said that they always planted on time; while 36% sometimes planted late and the rest always planted late. Most of the farmers who planted late cited lack of seed as the main reason that delayed their planting (Fig. 2.3).

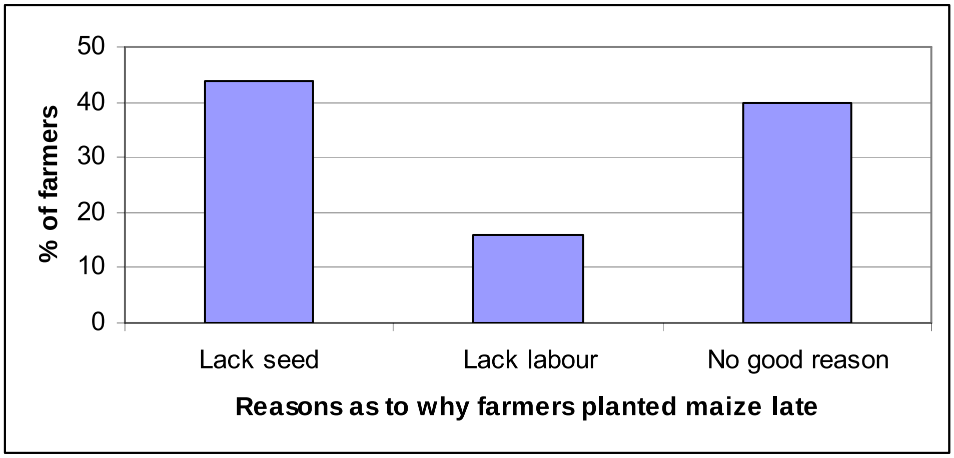

Fig. 2.3: Percentage of farmers who planted late as a result of a specific limitation

In cultivating their maize, farmers made effort to keep their fields weed free. However, lack of fertiliser was cited as a limiting factor to maize production in all the three districts while drought was cited as limiting in Luangwa (Region I) and Chibombo (Region II) districts.

During the 2003/04 agriculture season, 57.5% of the farmers had their maize crop attacked by pests but only 0.8% applied chemicals to control the pests. Nine percent had their crops attacked with diseases while 74.2% had weed problems. Farmers cited a number of difficulties they faced in producing a good crop of maize. These included; failure to access improved seeds, lack of cash or credit, lack of a source of improved seed cultivars, failure to apply fertiliser, weeds and disease problems. Food insecurity was 82.8% (Luangwa), 72.5% (Chibombo) and 70% (Lufwanyama).

Although maize was produced primarily for subsistence, limited quantities were marketed within rural communities or sold to the government through the Food Reserve Agency (FRA). However, buying of commercial maize grain by private companies was described as poor by 63.3% of the farmers. It was also found that the yield of maize were significantly correlated ($p \leq 0.05$) with good seed delivery of improved seeds ($r = 0.268^*$).

2.3.4 Factors influencing the uptake of improved cultivars

All farmers in Luangwa (Region I) cited drought as a major constraint to maize production while 85% said so in Chibombo (Region II) but none cited drought in Lufwanyama (Region III). On average, 88% cited low soil fertility as a constraining factor to maize production in the three districts. About 78% failed to apply NPK basal dressing fertiliser (65% in Luangwa, 83% in Chibombo and 85% in Lufwanyama); while about 84% failed to apply nitrogen top dressing fertiliser (65% in Luangwa, 93% in Chibombo and 93% in Lufwanyama).

About 46% of farmers in drought prone areas (Luangwa and Chibombo) believed that local cultivars were more tolerant to drought than improved cultivars, while 30% thought that their tolerance was similar. Of the farmers interviewed, 50% (Luangwa) and 42.5% (Chibombo) said that landraces tolerated drought more than improved cultivars, and this view was held by 34% of the stakeholders interviewed (Table 2.6). On tolerance to low soil fertility 15.0% (Luangwa), 32.5% (Chibombo) and 75% (Lufwanyama) believed that landraces were superior to improved cultivars, an observation held by 10% of stakeholders.

Participation in education exercises such as field schools and field days were also assessed as they impart knowledge to farmers on the benefits of improved agricultural technologies. Of the respondents, 47% (Luangwa), 70% (Chibombo) and 50% (Lufwanyama) had participated in at least one field day during the last 3 years. Although at such field days farmers were exposed to improved crop cultivars and other technologies, only a few (22%) planted improved seeds. However, the survey found that 87% of the farmers were aware of the availability of improved cultivars that could increase their farm production. It was also found that suitability of cultivars to local climatic conditions significantly ($p \leq 0.05$) correlated negatively ($r = -0.194^*$) to tolerance to drought.

Although the majority of the farmers planted local maize, 93% believed that improved maize cultivars yielded more than local cultivars. To ascertain why farmers preferred the local cultivars to improved ones, the best landrace was compared to the best improved cultivar a household would have preferred to grow (Table 2.6).

Table 2.6: Farmers experience on level of superiority of the best local cultivar versus the best improved cultivar grown

	District			
	Luangwa (%)	Chibombo (%)	Lufwanyama (%)	Mean
Resistance to pest and diseases	70.0	42.5	85.0	65.8*
Tolerance to drought	50.0	42.5	0.0	30.8*
Tolerance to low soil fertility	15.0	32.5	75.0	40.8*
Palatability	72.5	77.5	97.5	82.5*
Storability	90.0	90.0	95.0	91.7
Poundability	90.0	77.5	97.5	88.3*

* denotes that the districts differed significantly at $p \leq 0.05$

It was found that although farmers perceived landraces as low yielding, they believed that they were superior to improved cultivars in terms of resistance to pests and diseases (65.8%), tolerance to drought (30.8%), tolerance to low soil fertility (40.8%), grain palatability (82.5%), grain storability (91.7) and poundability (88.3%).

There were wide variations in the actual reasons that motivated farmers to plant local maize cultivars (Fig. 2.4). More than a third lacked cash or credit to purchase seed and other inputs; others cited availability, yield, flour quality, storability and possibility for recycling as major factors that persuaded farmers to plant local cultivars.

Most of the small-scale farmers interviewed (87%) believed that good improved maize cultivars were available in Zambia, but needed additional inputs to offset effects of stresses such as drought and low soil fertility. About 1% of the farmers believed that the available cultivars tolerated drought or low soil fertility. On seed delivery of improved seed to local areas, about 97% of the farmers said it was poor and agreed with 69% of stakeholders interviewed who also cited poor roads (leading to high transport costs), farmers being too scattered (making it costly for seed suppliers to reach them), provision of subsidized seed that was believed to conflict with seed delivery by the private sector, and low seed sales as major constraints.

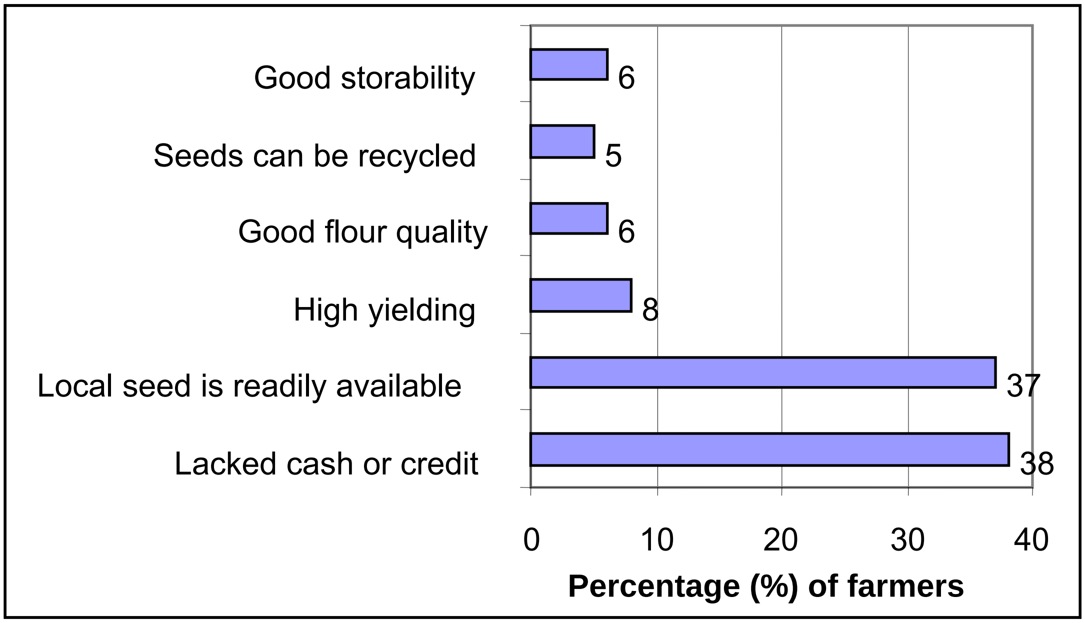

Fig. 2.4: Reasons cited by farmers that motivated them to grow local maize cultivars

High yield of maize correlated with large farm size of above 5ha (r = 0.263*) and larger size of households (r = 0.300*). Low maize yield obtained by farmers in the study areas correlated positively (r = 0.258*) with low tolerance to drought. Improved seed correlated negatively (r = -0.281*) with low yield, while use of landraces correlated positively (r = 0.265*) with low maize yields (Table 2.7).

The study found that only 17.5% (Luangwa), 27.5% (Chibombo) and 35% (Lufwanyama) were food secure. On average 73.3% of the farming households in the study areas were food insecure. Food security is negatively correlated with use of landraces (r = -0.603*) and positively correlated with the use of improved seeds (r = 0.578*).

In maintaining their landraces, farmers selected seed for planting based on some preferred characteristics. No farmer selected for superior plant characteristics while the crop was growing in the field. The study established that farmer selection was carried out at harvest and thereafter. Some farmers selected ears for seeds at planting (47%), while others selected ears at harvesting (29%) or at shelling for storage in bags (24%). The three most common selection criteria were flintiness (58%), followed by large grain size (27%) and long cob length (12%). Flintiness had a positive correlation with tolerance to drought (r = 0.197*) but its correlation with low soil fertility (r = 0.010) and high grain yield (r = -0.122) were non significant.

To identify factors associated with adoption and use intensity of the improved maize cultivars, various farm and farmer characteristics, as well as technological attributes were used in a Tobit model. The farmer characteristics that influenced adoption of improved cultivars included; farming experience, older age of household head (> 65 years), large households (>10 members), gender of head of household and contact with extension service (Table 2.8). However, none had a significant influence ($p \leq 0.05$) in causing farmers to adopt improved maize seed cultivars. Considering farm characteristics, only distance to input market, and access to credit influenced adoption of improved maize cultivars but neither had a significant influence ($p \leq 0.05$).

Table 2.7: Pair wise correlations of farmers’ perceptions of different types of maize cultivars, experience in maize production and their selection criteria for (* denotes data significant at P≤0.05)

	Grain yield (GY)			Seed planted											
	High	Low	Food secured	Improved	Landrace	Recycled	Long cob	Large grain	Flint	White grain	Drought tolerance	Tol. low soil fertility	Palat-ability	Store	Pound
High yield	1														
Low yield	-0.295*	1													
Food secured	0.098	-0.332*	1												
Improved seed	0.122	-0.281*	0.578*	1											
Landrace	-0.117	0.265*	-0.603*	-0.977*	1										
Recycle seed	-0.023	0.078	0.019	-0.066	-0.029	1									
Long cob	0.077	-0.117	0.074	0.177	-0.168	-0.045	1								
Large grain	-0.007	0.045	-0.023	-0.054	0.065	-0.074	-0.219*	1							
Flintiness	-0.122	0.095	-0.092	-0.142	0.124	0.106	-0.423*	-0.701*	1						
White grain	-0.017	0.058	0.152	0.170	-0.166	-0.011	-0.033	-0.055	-0.107	1					
Drought tol.	-0.043	0.144	-0.138	-0.124	0.127	-0.028	-0.083	-0.138	0.197*	-0.021	1				
Tol.low fertility	-0.039	-0.146	0.157	0.187*	-0.181*	-0.026	0.054	-0.126	0.010	0.440*	-0.048	1			
Palatability	-0.037	-0.144	0.178	0.143	-0.150	0.057	0.031	-0.020	0.003	0.042	-0.096	0.096	1		
Storability	-0.112	-0.056	-0.091	-0.126	0.119	0.037	0.016	0.114	-0.137	0.028	-0.069	0.063	0.258*	1	
Poundability	-0.077	-0.056	0.102	0.072	-0.078	0.045	0.051	0.043	-0.050	0.033	-0.155	0.076	0.789*	0.266*	1

Technological attributes such as high maize yield, need to apply fertiliser, selecting long cob, perceived superiority of local cultivars to improved ones in terms of yield, palatability, drought tolerance and low soil fertility were found were associated with adoption of improved maize cultivars. However, only need to apply fertiliser and drought tolerance was found to be significant. The study also found that food security had a significant influence ($p \leq 0.05$) with farmers adopting improved maize cultivars. Of the factors that had a significant influence with farmers adopting improved maize cultivars, food security had the largest influence ($p \leq 0.05$), followed by need to apply fertiliser and drought tolerance.

Table 2.8: Factors associated with adoption and use intensity of an improved maize cultivar

Use of improved maize seed	**Coef.**	**Std. Err.**	**P>|t|**
Farming experience	0.744	0.729	0.310
Age of household head (> 65 years)	0.705	0.587	0.232
Large households (>10 members)	0.297	0.512	0.563
Female headed households	0.199	0.317	0.530
Male headed households	0.175	0.345	0.614
Participation at field day	0.072	0.322	0.823
Contact with extension	0.120	0.311	0.701
Small household (1-5 members)	0.010	0.330	0.977
Distance to input market	0.709	0.499	0.158
Access to credit	0.058	0.386	0.881
Food security	1.684	0.345	0.000
High maize yield	0.296	0.621	0.635
Need to apply fertiliser (basal)	1.299	0.530	0.016
Selecting long cob	0.413	0.686	0.549
Local cultivar more yielding	1.131	1.003	0.262
Local cultivar more palatable	0.864	0.540	0.112
Local cultivar more drought tolerant	0.755	0.360	0.038
Local cultivar more tolerant to low soil fertility	0.554	0.382	0.150

2.4 Discussion

2.4.1 Demographic characterization of households

Although most of the farmers interviewed were married, in the active age (between 35 and 65 years), and had acquired experience in small-scale farming in their villages, they lacked knowledge to enhance their farming. Most of the farmers did not go beyond primary education and did not belong to farmer groups where they could learn about new technologies and enhance their farming. Probably farmers lacked knowledge for productive farming to ensure food security. This is confirmed by the significant positive correlation of food security with belonging to an association (0.212*). Although at least 50% of the farmers had attended a field day during the previous three years, the exercise was probably not adequate in isolation.

The significant negative association of young household head (16 – 35 years) with belonging to an association (r = -0.245*) and with contact with extension (r = -0.199*) shows that the young household heads did not belong to farmer groups where farmers learned skills for productive agriculture and, therefore, lacked skills in crop production. The significant correlation between food security and contact with extension (r = 0.205*) and with being a member to a farmer association (r = 0.212*) shows that such contacts and groupings enabled farmers acquire skills to produce more food. Small-scale farmers in rural areas should be organized in farmer groups for services such as training in developing their agricultural production.

It has been found that large families cultivated large farm sizes (>5ha), used seed of improved cultivars and obtained higher yields of maize. In order to obtain better returns, the improved cultivars responded to additional inputs such as fertiliser and irrigation. However, those who achieved high yield were weakly associated with access to credit (r = 0.064) and with use of improved seed (r = 0.122). High GY did not correlate did not correlate low weed problem but correlated large families (r=0.300*). Probably high labour units in large families enable such households weed their fields more successfully and achieve high yields.

The significant correlation between farming experience and weed problems (r = 0.346*) suggests that farmers applied animal manure such as cow dung in order to improve soil fertility. Continued crop cultivation without additional fertilisation could have depleted the soils of nutrients hence the need to add manure. However, the practice could have introduced weeds that were costly to control. It was also found that those who did not have weed problems had more regular contact with extension (0.365*) suggesting that the farmers could have learned some skills such as crop rotation to improve soil fertility and minimize weed problems in the field.

2.4.2 Access to resources

Despite the adequacy of land, most farmers cultivated their crops on small fields as they lacked cash, credit and market access to purchase farm inputs. Input provision in rural areas is poor partly because of the poor infrastructure in the isolated areas. This was confirmed by the revelation of stakeholders interviewed that seed marketing in rural areas was poor and that a trader in seeds in such areas was not likely to make profits. There is also a counter argument that seed availability might create demand for other inputs in these remote localities, and this requires further research.

Much of the seed accessed by farmers was of local unimproved cultivars, obtained from within their local communities and saved from a previous harvest. Farmers accessed the seed through their own savings (69%), gifts (9%) or sales (22%). The fact that about 22% of the local seed was marketed shows that a seed market for a preferred maize cultivar did exist in the rural areas and could be developed further.

Lack of access to credit was found to be an important limitation to farmers' use of improved cultivars, and motivated them to plant landraces. This meant that farmers lacked resources with which to purchase inputs and confirmed findings of the PRA. It is also in agreement with findings of Mungoma and Mwambula (1997) that withdrawal of fertiliser subsidies in Zambia reduced application of fertiliser by farmers.

Those who planted large fields (> 5ha) were generally nearer to the input markets, planted more improved than local cultivars, and achieved higher yields. The findings implied that farmers with more access to resources were able to cultivate more land, purchase improved seed, and were rewarded with higher yield. Increased access to markets could revolutionize agriculture in the country because farmers would purchase better seed, crop more land, and perhaps buy more fertiliser and hire extra labour to weed crops. The negative correlation between food security and lack of credit (r = -

0.306*) and with use of unimproved local cultivars (r = -0.603*) and the positive correlation of food security with use of improved cultivars (r = 0.578*) suggests that if more farmers planted improved cultivars their yields could improve. Therefore, the continued dependence on landraces will slow the rate of improvement in farmer yields.

2.4.3 Crop production

Although maize was the most important food crop to farmers in the study areas, farmers also cultivated groundnuts, cotton, soybeans, cassava, sweet potato, sorghum, millets, beans and paprika to support their subsistence. Yet despite the fact that farmers cultivated a number of crops, there was a general consensus that farm incomes per household were too low to meet household needs. The farmers usually failed to purchase agricultural inputs (seed, fertilisers and irrigation) and obtained maize yields reported to be as low as 0.58t ha^{-1} (CSO 2006).

In spite of being aware of the existence of improved maize cultivars that yielded high when recommended crop management practices were followed, most farmers did not plant them (Table 2.3). Probably, they did not believe that improved cultivars were superior to the local ones when cultivated under low fertility and drought. This belief has not created a market for improved seeds in rural areas and has contributed to the continued poor availability of improved seed.

Almost half of the stakeholders doubted farmer preferences for improved maize seed. They felt that farmers did not want to spend on seed because they had an alternative in the landraces. Seeds of the landraces were less expensive, and were readily available through savings from previous harvests (67%) while 22% was procured from within the local community and about 11% accessed through gifts. The revelation that about 22% of the farmers bought landraces (though at lower price than at a formal seed market) showed that farmers were able to spend on seeds and could buy seeds of improved cultivars when convinced that they were good. The findings that about 68% of the farmers who planted improved seeds accessed them through relief programmes by government and/or non-governmental organizations (NGOs), while only 20% accessed the seeds through private traders, suggests that much needs to be done to convince farmers to spend on seed of improved cultivars. Provision of cultivars that address farmer constraints such as drought and low soil fertility could motivate farmers to invest in improved seed. However, the provision of relief seed by government and others should be in the form of credit, so that the programmes complement further development of the seed market in rural areas. Further research is required on how to develop the seed market in rural areas where farmers are sparsely distributed.

Although farmers prepared their land for planting early enough to plant with the first rains, less than half (41%) planted early as most of them lacked seed. It also means that some farmers consume much of their harvest and these look for seed to plant. This also implies that availability of seed of landraces and improved cultivars was low in the study areas and confirms findings of this study that the potential for a seed market does exist in rural areas. It was established that in cultivating their maize, farmers made an effort to keep their fields weed free but lacked fertiliser (in all the three districts) and irrigation in Luangwa (Region I) and Chibombo (Region II) districts. Therefore, appropriate cultivars, superior in tolerance to low soil fertility, should be developed for the respective areas.

Farmers who planted seeds of improved cultivars did not necessarily enjoy high yields implying that some improved cultivars were not adaptable or farmers failed to exploit them to achieve high yields or both. The findings suggest that enhancing seed delivery of improved seeds alone may not be an adequate strategy to increase maize yields among the farmers. Farmers apparently failed to control some stresses such as poor soil fertility, drought and weeds which were found to be common limiting factors to maize production in the affected areas. Provision of cultivars that tolerate drought and low soil fertility offers a probable solution to the problem. However, even a low fertility tolerant cultivar will remove nutrients from soils which may limit production eventually measures were not put in place to enrich the soils. Practices such as crop rotation, conservation farming and modest use of fertilise among others, should be promoted among farmers.

2.4.4 Factors influencing the uptake of improved cultivars

Drought was more limiting to maize production in Luangwa (Region I) than in Chibombo (Region II) but was not a constraining factor in Lufwanyama (Region III). In order to enhance maize production in the two areas, cultivars recommended for production under Region I should be more drought tolerant than those recommended for Region II. Bunyolo et al. (1997) also reported that drought in Region I was more severe than that in

Region II. It was also found that low soil fertility constrained maize production more in Lufwanyama than in Chibombo where it was also more constraining than in Luangwa. The current general fertiliser recommendation across the whole country requires a review so that regional differences in fertiliser needs are reflected in recommendations, and scarce and expensive nutrients are conserved.

Only 24% of farmers in drought prone areas (Luangwa and Chibombo) believed that improved cultivars were more tolerant to drought than landraces, while only 23% believed that they were more tolerant to low soil fertility. The findings mean that most farmers doubted superiority of improved cultivars over local landraces in tolerance to abiotic stresses and that this has contributed to the low adoption of improved cultivars. It challenges plant breeders to develop varieties with convincing superiority to abiotic stresses. It seems sensible that such a breeding programme should consider improving the local landraces for yield and stress tolerance in order to take advantage of any preferred superiority that they possess.

Farmer education exercises such as field schools and field days imparted knowledge to farmers regarding improved agricultural technologies. At field days farmers are exposed to improved crop cultivars and other technologies. Although most farmers participated in field days and were aware of the availability of improved cultivars that could increase their crop production, adoption of the same was low. Suitability of the cultivars to local climatic conditions correlated negatively ($r = -0.194^*$) with tolerance to drought meaning that farmers considered the improved cultivars unsuitable. It was also found that although farmers perceived the local cultivar as low yielding, they believed they were superior to improved cultivars in terms of resistance to pests and diseases, tolerance to drought, tolerance to low soil fertility, grain palatability, grain storability and poundability. Among reasons that de-motivated farmers from planting seeds of improved cultivars were lack of cash or credit, poor seed availability, low grain yield under low inputs, poor flour quality and poor storability. Therefore, in developing cultivars targeting the small-scale farmers in the study areas, farmer preferences and perceptions should be taken into account as they are important in influencing the adoption of cultivars. The findings also imply that market development of both seed and produce should also be prioritized when improving maize production by farmers in rural areas.

It was found that most of the maize cultivars available in Zambia were not considered tolerant of stresses such as drought and low soil fertility. This has not helped in developing a seed market in rural areas where farmers desire cultivars that tolerate these stresses. Further, poor roads and the provision of subsidized seed do not help in developing a viable seed market. In order to enhance the provision of improved seed to small-scale farmers in rural areas, strategies employed should address issues of increasing the availability of seeds that address specific concerns of small-scale farmers such as those with ability to yield well under low input conditions.

High yield of maize correlated positively with larger size of households (r = 0.300*) and good contact with the extension service (r = 0.136). The huge pressure to feed a large household motivated members to seek advisory service from the extension service which improved their farming practice, hence the high yield of maize. It was also found that farmers who cultivated maize for more than 10 years in the local area had higher yields than newer farmers because they had acquired experience in cultivating maize in the local area. Farmers with local experience of cultivating maize may have practiced seed selection that could have improved the yielding ability of local cultivars over the years. This agrees with Louette and Smale (2000) who reported that over many generations farmers have been altering the genetic makeup of the crops they grow through selection for mainly ear and kernel characteristics.

The low maize yield achieved by farmers in the study areas correlated positively (r = 0.258*) with low tolerance to drought meaning that drought limited maize production among small-scale farmers in rural areas. Provision of drought tolerant varieties in such areas could contribute to increasing maize production. Use of unimproved local maize seeds correlated positively (r = 0.265*) with low maize yields meaning that use of local unimproved cultivars contributed to low maize yields obtained by farmers. Therefore, the continued use of local seeds by small-scale farmers will not improve their returns. This calls for appropriate interventions to improve their maize production.

The study found that most households in the study area were food insecure. Food security was negatively correlated (r = -0.603*) with use of local maize cultivars and low yields of maize (r = –0.332*) meaning that when farmers planted local maize cultivars, they tended to obtain low yields that led to food insecurity. The finding that food security was significantly correlated with those who planted improved seeds (r = 0.578*) apparently confirms this. In order to increase food security in the rural areas effort should be made to provide improved seeds. With an estimated 1 million small-scale farmers in Zambia, the government run Fertilizer Support Programme under which about 125000 small-scale farmers receive support for fertiliser and improved seeds for cultivation of about 1ha of maize each (MACO, 2005), though appreciated, is inadequate. Other inputs such as irrigation, not provided in the support, still limit the productivity of the maize crop.

To maintain their landraces, farmers selected seed for planting based on preferred grain and ear characteristics after harvest. This kind of selection is not very effective because some superior plant characteristics such as ears per plant, tassel size, anthesis-silking interval and leaf senescence that are important in identifying genotypes superior in tolerance to the abiotic stresses can only be observed while the crop is growing in the field (Banziger et al., 2000) where the competitive situation among plants can be observed. Selecting genotypes based on flintiness, grain size and ear length does little to improve stress tolerance. The significant positive correlation of flintiness with tolerance to drought (0.1972*) suggests that selecting for flintiness could improve tolerance to drought. However, information on its heritability, gene action and correlation with grain yield does not support this. In general farmer selection in the study areas was not effective in enhancing maize yields of their local maize because these too yielded low. However, selecting for flintiness and long cobs of maize could be investigated further for effectiveness in enhancing tolerance to either drought or low soil fertility.

The finding that selection of disease/pest free seeds at harvest was positively correlated (r = 0.572*) with use of chemical control suggests that selecting disease/pest free seed grains was not adequate as disease free grains may not only be due to resistance to the disease but also absence or mild attack of the same. Some diseases are seed borne and may not be identified by the clean look of grains. The correlation could also be due to the fact that farmers are more likely to select for disease/pest resistance in environments that have greater disease and pest pressure. Use of chemical control would also be greater in these environments. To develop disease resistant genotypes, plants should be observed throughout the growing season and selection for superior genotypes should be carried out when the attack by pest/disease is well manifested.

All the local unimproved cultivars in the study areas were predominantly of white colour. African farmers have been selecting for white grain colour of maize over generations. The study also revealed that the use of white grain colour as a selection criteria correlated positively with tolerance to low soil fertility ($r = 0.440^*$) and low weed problem ($r = 0.400^*$). This correlation could imply that white maize was superior in tolerance to low soil fertility and competed well with weeds. However, grain colour is simply inherited and it is not too likely to have a pleiotropic effect on drought tolerance or ability to compete with weeds. Genetic correlations can also occur due to population structure (linkage disequilibrium) – white populations may have a longer history in the region and therefore have better adaptation. Yellow genotypes may tend to be newer introductions. These associations may be amenable to selection for a while, but the disequilibrium will dissipate over time.

Of the factors that influenced adoption and use intensity of the improved maize cultivars, none of the farm, nor farmer characteristics had a significant influence ($p \leq 0.05$). However, need to apply fertiliser, drought tolerance and food security had significant influence. Of these, food security had the largest influence followed by need to apply fertiliser and drought tolerance. These findings mean that farmers viewed low soil fertility and water stress as major constraints to maize production. The two played a major role in influencing adoption of improved cultivars. The significant influence of food security means that farmers will adopt an improved cultivar that increases their food security. Therefore, ability to tolerate low soil fertility and drought would enhance farmer adoption of improved cultivars, only if such technologies increased crop yields under all growing conditions and enhanced food security.

2.5 Implications for breeding research and conclusions

Notwithstanding the fact that there were many suppliers of improved seed cultivars in Zambia, availability of the cultivars in rural areas was poor and most farmers depended on local landraces. It has been found that the low uptake of improved cultivars among small-scale farmers was partly due to their poor performance under farmer conditions. Most farmers cultivated their maize under conditions of some stress and failed to exploit the potential of a cultivar. Factors that limited maize production by small-scale farmers in the study areas included drought, low soil fertility, pests/diseases and weeds. Palatability, grain storability and poundability were also important characteristics preferred by farmers. These should be taken into account in developing cultivars targeting small-scale farmers.

Small-scale farmers in Zambia obtained low yields, whether they planted local or improved seeds. For example, a cultivar that yields over 10t ha^{-1} at research stations, achieved no more than 1t ha^{-1} under cultivation by small-scale farmers (Zambezi and Mwambula, 1997). One might attribute the low yields to abiotic stresses farmers were unable to control. Most improved cultivars have resistance to biotic stresses prevalent in Zambia and considerable effort has been made to overcome abiotic stresses. However, drought and low soil fertility are still major abiotic stresses limiting farmer production of maize. In general the maize crop grows under conditions of stress and the stresses prevalent at farm level should be minimized. This may be achieved either by farmers producing crop cultivars following recommended practices of the cultivar, or breeders developing cultivars whose yield is high and stable under low input (stress) conditions.

Most small-scale farmer perspectives, and that of key stakeholders, on released cultivars were that improved cultivars were good if they were provided with inputs required to maximize their productivity. Unfortunately, most small-scale farmers in Zambia cannot afford inputs to maximize crop yields of maize. Therefore, cultivars need to be developed that yield well when maize is grown under stress conditions observed at farm level. Such cultivars should also incorporate other preferred characteristics by farmers such as flintiness. Although the survey indicated that correlations of yield with flintiness, large grain size and long cob size were poor, flintiness was associated significantly with drought tolerance. A field study is required to investigate flintiness in relation not only to maize yield but also to varietal tolerance to drought and low soil fertility. Incorporating tolerance to low nitrogen would be critical as the survey found that failure to apply top dressing nitrogen fertiliser was a major constraint limiting maize production in the study areas.

Although the study found a number of constraints that limited maize production by small-scale farmers, developing tolerance for all the stresses may not be achieved in a single cultivar. However, when the provision of a cultivar tolerant to a specific stress was accompanied by appropriate crop husbandry practices to minimize other stresses, small-scale farmers could increase their yields.

Breeding of maize cultivars that tolerated drought should only target Regions I and II while that of low soil fertility should target all the three agro-ecological regions of the country. Such cultivars should be developed preferably within the respective environment to enhance adaptability of the genotypes to the respective stresses. Use of local germplasm is advisable as indications from the survey were that the unimproved local cultivars (landraces) had some inherent ability to tolerate the stresses.

In Zambia, candidate cultivars are assessed by a government institution, Seed Control and Certification Institute (SCCI) under high input conditions in the three agro-ecological regions. Only cultivars found to be superior are released to the farming community for commercial production. In order to identify cultivars that perform well under abiotic stress conditions, SCCI should test candidate cultivars under both high and low yielding conditions prior to their release. Cultivars found to be good should be released for a specific environment in Zambia. This will ensure that farmers are provided with cultivars that best fit their crop environment. It was also the concern of 62% stakeholders that the two year period it took to test and release a cultivar was too long. Measures to improve cultivar testing should not cause further delays in introducing the new technologies to farmers. SCCI should periodically publish a list of recommended crop cultivars for specific environments. Such information should be disseminated to the farming community through the MACO structure throughout the country.

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Appendices

Appendix 2.1: Check-list for the Participatory Rural Appraisal

Livelihood strategies and food security

1. List and rank your livelihood strategies.
2. How do you describe distance to input market
3. Discuss and rate your food security

Farming practice

4. How do you prepare land for planting?
5. Describe your access to market of farm produce?
6. How often are field days held in your area?
7. Discuss and compare your local and improved maize seed
8. Identify reasons why farmers plant local seed
9. List and rank criteria used to select your local maize seed for planting
10. List constraints to maize production

Appendix 2.2: Questionnaire for farmer survey

Name of Interviewee ……………………………………Sex…………………………………….

Province ………………………………………………District…………………………………….

Camp …………………………………………………Village…………………………………

Latitude...South…………………………………………Longitude……East..………………..

Altitude……………………………Metres above sea level………………………………………

Interviewed by……………………………………Date……………………………………………

A. Farmer Household Description

1. Sex of household head (HH)....... 1. Female 2. Male

2. Marital status of head: 1. Married 2. Single 3. Widowed 4. Divorced 5. Separated

3. Age of household head: 1. 16-35 Years 2. 35-65 Years 3. Above 65 Years

4. Years of residence in the village 1. < 5 Years 2. 5 - 10 Years 3. > 10 Years

5. HH is a member of any farmer group: 1. Yes (Specify) ………2. No (Why not)……….

6. Educational level of head: 1. None 2. Primary School 3. Secondary School 4. Above Secondary School

7. Household composition

	Age group	**Total number**
7.1	Under 5 Years	
7.2	5-15 Years	
7.3	15-65 Years	
7.4	65 Years and above	
7.5	Total	

7.6 Adequacy of family labour in the households to cultivate a crop 1. Adequate 2. Not adequate

8. Contact with Extension officers 1= Good 2=Rare 3=Absent (bad)

B. Livelihood Strategies And Security

9. What are the household’s livelihood strategies?

SN	**Livelihood Strategy**	**Rank 1 to 9 (1=most important, 9=least important)**
1	Crop production	
2	Animal production	
3	Poultry production	
4	Fruit and vegetable production	
5	Charcoal burning	
6	Fishing	
7	Trading	
8	Waged labour	
9	Other ……………………	
10	None	

10 Size of farm: (tick only 1)

1. less than 2ha 2. 2-5ha, 3. More than 5ha

11 Distance to source of inputs (tick only 1)

1. Within 5km 3. 20-50km 4. More than 50km
2. 5-20km

12 Is the household food secure i.e. has food from one harvest to another (tick only 1)

1. Yes 2. No

C. Farming practice

13.0 Farming capital (labour and credit)

13.1 Adequacy of land for farming by the household (tick only 1)

1. Yes 2. Fair (if hired) 3. No

13.2 Access to credit

1. Yes 2. Fair (if irregular) 3. No

14.0 Crop husbandry

14.1 Land preparation is done by: (tick only 1, if more then rank them)

1. Tractor 2. Ox-drawn Plough 3. Hand tillage using a hoe 4. No tillage
5. Other (specify)

14.2 Planting on time (tick only 1)

1. Always on time 2. Sometimes on time 3. Always late

15. If late, reasons for late planting (tick only 1, if more then rank them)

1=Seed not available 2=Lacks labour 3=Other (specify) 4=None

16.0 Major crops grown

16.1 Name and rank two major crops grown (1= most important)

1=Maize, 2=Cassava, 3=Sweet potato, 4=Sorghum, 5=Millets, 6=Groundnuts, 7=Beans, 8=Soybeans, 9=None, 10=Cash crops (paprika, Irish potato, sunflower, cotton)

a) Number 1 crop = b) Number 2 crop =

16.2 Access to market for farm produce

a) No. 1 crop 1=Good, 2=Fair, 3=Poor
b) No. 2 crop 1=Good, 2=Fair, 3=Poor

17. Seed availability of the main food crop in your area (tick only 1)

a) No. 1 crop	1=Good,	2=Fair,	3=Poor
b) No. 2 crop	1=Good,	2=Fair,	3=Poor

18 Participated in a field day in the last 3 years (tick only 1)

1=Yes, 2=No

D. Technology (Seed) Specific Attributes

19.0 Crop production by household

19.1 Does the household produce enough food for itself: 1=Yes or 2= No

19.2 Compare your local and improved maize seed. When you grow maize;
Do you think local maize yield lower than improved cultivar: **1**=Yes or **2**= No

19.3 Rank 2 most critical problems encountered if you use improved seed maize.

SN	Item	1=biggest problem
1	Distance to local seed source	
2	No local seed source	
3	Failure to buy seed	
4	Low yields	
5	Fertiliser not available	
6	Fail to buy fertiliser	
7	Disease problem	
8	Drought problem	
9	Lack cash or credit	
10	Post harvest losses	
11	Poor poundability	
12	Lack labour	
13	Lack grain market	
14	Too hot weather	
15	Other (specify)	
16	None	

19.4 Choose the most critical problem encountered in provision of improved maize seed in your area.

SN	Item	1=biggest problem
1	Improved seed arrive late	
2	Few farmers buy improved seed	
3	Farmers prefer to plant local seeds (good storability, poundability)	
4	Farmers prefer local seeds (better with no fertiliser than improved seed)	
5	Farmers prefer local seeds (better in drought resistance than improved seed)	
6	Long distance to sources of seed	
7	High seed price	
8	None	
9	Lack fertiliser	

19.5 What was the source of maize seeds you grew last season (2003/4)?

	19.5 Seed type 1=Improved seeds 2=Local seeds 3=Recycled seeds	**19.6 Seed source** 1. Own saved improved seed 2. Own saved local seed 3. Private seed trade 4. Gift seed local 5. Bought local seed 6. Provided improved seeds by relative and friends 7. Relief seed by government or NGOs
Main maize field		
No. 2 maize field		

20. Consider provision of improved seeds with respect to small-scale farmers. How do you rate released cultivars

		1=Good, 2=fair, 3=bad
20.1	Type of maize cultivars released	
20.2	Suitability of cultivars for small-scale farmers	
20.3	Wanted cultivars release on time	
20.4	Seed delivery to farmers	
20.5	Cultivar suitability for your soil type	
20.6	Cultivar suitability for your local climates	
20.7	Cultivar tolerance to drought	
20.8	Cultivar tolerance to low soil fertility	

21. Provide three (3) reasons for growing the local cultivar. – Rank the reasons

	Reason	Rank (1=best reason)
1	Improved seed not readily available	
2	Improved seed available but fertiliser not available	
3	Lack of market for maize grains	
4	Local seed yield better than improved seed under drought	
5	Local is good to process for food	
6	Local cultivar stores better than hybrid	
7	Flour quality is better	
8	Lack cash/credit to buy seeds and fertiliser	
9	Poor availability of seeds	
10	Poor availability of fertiliser	
11	Local seeds yield better than improved seed under low soil fertility	
12	Local seeds is readily available	
13	Local seed has high resistance to flooding	
14	You can recycle local seeds	
15	Resistance to pest and diseases	
16	None	

22. Selection of your seed from your local maize.

22.1 When do you select seeds for planting from your local maize crop

1= While the crop grows in the field, 2= At harvesting, 3=At bagging, 4=At planting, 5= Do not select

22.2 **Select and rank the top 3 criteria you use to select your local seeds for planting**

		Rank = 1 most preferred
1	Good Standability	
2	No Lodging	
3	Good Plant height	
4	Prolificacy (more cobs/plant)	
5	Less Leaf roll	
6	Leaf orientation	
7	Green leaves after flowering (leaf senescence)	
8	Stem colour	
9	Early tasseling	
10	Early silking	
11	Early maturing	
12	Tassel size	
13	Large Cob size	
14	Large Grain size	
15	Good Storage	
16	Flintiness (Grain type)	
17	Good Poundability	
18	Disease/pest resistance	
19	Grain colour	
20	Other	
21	None	

1. Why do you select seeds

1=To plant seeds that can germinate, 2=To produce similarly large grains
3=To produce maize grains that I like, 4=To produce similarly cob size
5=To produce grains of the colour I want 6=To produce maize grain of the taste I want
7=Other (specify)………………………… 8=None

24. Rate the following characteristics in terms of your experience in maize production (in the last 2003/04season).

		1 = High, 2 = Medium 3 = Low to none
24.1	How good was your maize yield High= > 4t ha^{-1}, Medium=1-4t ha^{-1} Low= < 1t ha^{-1}	
24.2	How serious was the problem of pest attacking your crop	
24.3	How serious was the problem of disease on your crop	
24.4	How tolerant was your maize crop to drought	
24.5	How tolerant was your maize crop to low Nitrogen	
24.6	How serious was the problem of Weeds in your maize field	
24.7	How much chemical control of diseases & pests was done (per ha)	
24.8	How much basal Fertiliser did you apply (per ha)	
24.9	How much top dressing fertiliser did you apply	

25 Compare the best maize cultivar grown by the household and that not grown (but wanted) by the household in terms of the following characteristics. (tick)
Best grown cultivar …………………….. Most wanted cultivar but not grown…………..

	1=Best grown is higher, 2= Same, 3= Best grown is lower
25.1 Yield	
25.2 Resistance (pest/disease)	
25.3 Tolerance to drought	
25.4 Tolerance to low fertility	
25.5 Palatability	
25.6 Storability	
25.7 Poundability	

26 Compare your best local cultivar grown with the best improved cultivar that you have ever grown in terms of the following characteristics. (tick)

	1=Best local is higher, 2= Same, 3= Best local is lower
26.1 Yield	
26.2 Resistance (pest/disease)	
26.3 Tolerance to drought	
26.4 Tolerance to low fertility	
26.5 Palatability	
26.6 Storability	
26.7 Poundability	

Appendix 2.3: Questionnaire for key stakeholders

1. Identification

Name of stakeholder……………………………………………………………………………….

Organization …………………………………………………………………………………….….

Position ………………………………………………………………………………………..….

Organization is involved in: tick:
1. Breeder, 2. Cultivar Release Committee 3. Seed production
4. Policy 5. Seed delivery 6. Other specify

District………………………… Interviewed by ……………………………….….

Date …………………………………………………………………………………………………

2. What are the household's livelihood strategies of people in rural areas?

Livelihood Strategy	Rank: 1 = very important
Crop production	
Animal production	
Poultry production	
Fruit and vegetable production	
Charcoal burning	
Fishing	
Trading	
Waged labour	
Other ……………………	

3. Rank items your organization bought from farmers in the last 12 months

	Rank in terms of market value 1=Most bought
Maize	
Cassava	
Sweet potato	
Sorghum	
Millets	
Groundnut	
Beans	
Others specify	
None	
Not applicable	

4. Rank items your organization sold to farmers in the last 12 months

	Rank in terms of market value 1=Most sold
Maize seed	
Cassava planting material	
Sweet potato planting material	
Sorghum seed	
Millets seed	
Groundnut seed	
Beans seed	
Others specify	
None	
Not applicable	

5 List and rank top maize seed cultivars sold to farmers by your organization in the previous season

	Name of a Cultivar (of those listed in 4 b below)	**Rank 1= most sold**
1		
2		
3		
4		
5		
6		
7		
8		
9		

6 How can you describe farmers' demand for seeds.

Answers 1= very high, 2 = high, 3 = fair, 4 = low, 5 = Very low

7. Consider provision of improved seed cultivars with respect to small-scale farmers. How do you rate released cultivars:

	Good (1)	Fair (2)	Bad (3)
Type of the maize cultivars			
Suitability for small-scale farmers			
Wanted and cultivars release on time			
Seed delivery to farmers			
Cultivar suitability for different soil types			
Tolerance to drought			
Tolerance to low soil fertility			

8. Objectives of maize breeding programme in your organization in addition to yield

	Objective	Rank them 1 to 10 (1= most common, last = least common)
1	Plant height	
2	Disease resistance	
3	Protein content improvement	
4	Tolerance to low nitrogen (Nitrogen use efficiency)	
5	Drought tolerance	
6	Tolerance to soil acidity	
7	Prolificacy (more ears/plant)	
8	Maturity period	
9	Grain type (Flintiness)	
10	Other (specify)	
11	Not applicable	

9.0 Rank problems with seed provision to smallholder farmers in rural areas

SN	**Item**	**Rank: 1=biggest problem**
1	Poor roads (infrastructure) - transport cost is high	
2	Farmers are too scattered - difficult to reach them	
3	Seeds sales are low – not profitable	
4	Cultivar not appropriate for small-scale farmers	
5	Needed cultivars are delayed in release	
6	Other (specify)	

10. Compare maize seed provision to farmers in urban and rural areas

SN	Item	Tick where Answer = High	
		Urban areas	Rural areas
1	Seed price		
2	Seed availability		
3	Accessibility		
4	Seed selling points		
5	Closeness to seed selling points		
6	Fertiliser availability		
7	Fertiliser price		
8	Closeness to fertiliser selling points		
9	Profitability by seed company		
10	Maize grain price		
11	Closeness to grain market		
12	Other (specify)		

Appendix 2.4: Number of farmer groups and farmers interviewed in the PRA and survey

District	Camp	Village/farmer group	Farmer group interview	Personal interviews	Field research assistance
Luangwa	Kaunga B	Mulamba	1	10	Queen Mpuka
Luangwa	Kaunga B	Mpona	1	10	Queen Mpuka
Luangwa	Chitope	Linga	1	10	Kalima Gwali
Luangwa	Chitope	Kalikumbula	1	10	Kalima Gwali
Chibombo	Liteta	Liteta	1	10	Getrude Akebu
Chibombo	Liteta	Nkoloma	1	10	Getrude Akebu
Chibombo	Keembe	Chilunga	1	10	Isaac Silinda
Chibombo	Keembe	Kotti	1	10	Isaac Silinda
Lufwanyama	Kampundu	Mibenge	1	10	Josphat Melele
Lufwanyama	Kampundu	Kapimbe	1	10	Josphat Melele
Lufwanyama	Mikuta	Lukwamuna	1	10	Henry Chomba
Lufwanyama	Mikuta	Manuel	1	10	Henry Chomba

Chapter 3: Genotype x Environment Interaction effects of maize genotypes under contrasting levels of soil fertility and agro-ecological regions

Abstract

In Zambia, farmers often grow maize cultivars under low fertiliser application in the three agro-ecological regions. This study investigated performance of nine popular cultivars under contrasting levels of soil fertility across the natural environments. The cultivars, comprising three commercial hybrids, three open pollinated varieties (OPVs) and three landraces, were evaluated under four fertility levels; nil, basal only, top only and recommended (basal and top) fertiliser applications at six environments (ENVs), two representing each of the three agro-ecological regions in Zambia. Fertilisation x genotype interaction effects, were significant in three of the six ENVs. This indicated that the cultivars were not stable cross all the fertility levels and ENVs. Fertilisation and cultivar effects were significant ($p \leq 0.05$) for grain yield (GY) at all the six ENVs. Cultivars achieved highest GY at Chilanga (Region II), and lowest at Luangwa (Region I). At Luangwa GY was 13% and 22% of GY achieved at Chilanga and Masaiti (Region III), respectively. At Masaiti cultivars achieved 73% of GY achieved at Chilanga. This trend was consistent with expectation because yield potential is highest in Region II and lowest in Region I. Based on average rank of GY across ENVs and fertilizer treatments, the five highest yielding cultivars were MRI724, Gankata, MM603, Kazungula and Pandawe (in that order). Yield increase as a result of applying fertiliser was 99%, 24%, and 41% under recommended, basal only and top only fertiliser treatments, respectively. MRI724 yielded highest under basal only, top only and nil fertilisation while a landrace (Gankata) yielded highest under full fertilizer application. In general landraces out-yielded OPVs and two hybrids under all fertiliser treatments. The trend was similar across the six ENVs. Implications for breeding, variety release policy and input subsidy scheme in Zambia are discussed.

Key words: Maize, genotype, environment, fertilisation, tolerance, stress

3.1 Introduction

Maize is the most important food crop in Zambia and is cultivated by 86% of the agricultural households (CSO, 2005) of which over 90% are small-scale farmers (CS0, 2006a). Maize yields obtained by small-scale farmers are poor (Chapter 2) and the country's average yield is only about 1.8t ha^{-1} (CS0, 2006b) while yields of about 10t ha^{-1} are achievable at research stations in southern Africa (Zambezi and Mwambula, 1997) and 22t ha^{-1} are obtainable in temperate environments (Loomis, 1997). Low soil fertility has been cited as one of the major constraints to maize production among resource poor small-scale farmers not only in Zambia but in the whole of southern Africa (Zambezi and Mwambula, 1997). In Zambia, the savanna soil contains low levels of nutrients (Bunyolo et al., 1997), and adequate fertilisers should be applied to boost soil fertility in order to exploit the yield potential of cultivars being released by breeders. Lack of nutrients and moisture cause stress on plants which respond by reducing yield.

Low grain yields obtained in the smallholder sector are due to abiotic and biotic stresses under which much of the maize is cultivated. This implies that the varieties lack tolerance to stresses prevalent on-farm, including low soil fertility. Banziger and Diallo (2004) observed that breeders developed varieties under optimal condition but farmers cultivated them in sub-optimal environments. They described the crop environment for farmers in eastern and southern Africa as one of low fertilisation, no irrigation, few pesticides, and delayed planting and weeding. Tolerance to stress is a measure of the plant's ability to mitigate the impact of the stress on the physiological processes involved in resource capture and utilization (Tollenaar and Lee, 2002). Therefore, the difference between potential and actual yield provides one measure of the lack of stress tolerance in a genotype.

Most farmers in Zambia cultivate maize under low soil fertility. Only about a fifth of the maize cultivated in the country during the 2005/06 season (CSO, 2007) was fertilised. About 60% of the small-scale farmers failed to apply basal dressing fertiliser and 54% did not apply top dressing fertiliser in Luangwa, Chibombo and Masaiti districts during the 2004/05 season (Chapter 2). The failure by farmers to apply fertiliser results in low yields and household food insecurity. The challenge for breeders in Zambia is to develop cultivars that are stable and maintain high yields under low soil fertility conditions.

Much of the maize breeding is conducted under high input conditions where environmental deviation is minimized meaning that the phenotype largely reflects the genotype (Banziger et al., 1997). Under such conditions heritability and genotypic variance are high, because the genotype x environment interaction and environmental variances are minimized, thereby enhancing a breeder's ability to identify desirable characteristics that enable breeding progress. Similarly, in evaluating candidate varieties, the seed certification Authority, Seed Control and Certification Institute (SCCI) of Zambia assesses the candidate varieties for value for cultivation and use (VCU) under recommended agronomic practice such as recommended fertilisation. Results of varietal evaluation by SCCI are considered for a decision by a broad based Variety Release Committee representing various interest groups in agriculture. Varieties that have high performance under these conditions are released for commercial production in Zambia. About 155 maize varieties have been released (SCCI, 2007), but only a few have been adopted by small-scale farmers (Chapter 2). This suggests that their performance under low input conditions in different ecologies has been unimpressive.

A cultivar improved under one environment may not be superior in another environment. When selection is carried out under good conditions will the improvement be carried over to poorer crop environments? Do cultivars that perform well in official release trials conducted under high fertiliser exhibit the same superiority when grown under low fertiliser under which most small-scale farmers cultivate their maize in Zambia?

Differential genotypic expression across environments is known as genotype x environment interaction (GE) (Fox et al., 1997). The existence of GE may mean that the best genotype under one environment may not be the best in another. Therefore, a genotype with significant GE interaction effects for GY is not stable for GY across environments and will perform best under a specific environment that best fits it. Such genotypes may also be useful in developing cultivars targeting low fertility conditions. A superior genotype that has non-signification GE interaction effects for GY is stable for the trait, and may be cultivated across environments (Romagosa and Fox, 1993). Low adoption of improved maize cultivars in Zambia suggests that the cultivars lack GY stability across environments in the country. It also implies that the cultivars may lack genes that lead to improved performance under low inputs.

Sibale and Smith (1997) observed that large genotype x environment interaction effects for grain yield (GY) under low nitrogen limited the value of selection under that abiotic stress. Reeder (1997) reported that in maize under stress mean GY and genetic variance of maize are reduced but GE increased. This means that the environment masked the expression of genotypic differences and the discrimation of genotypes based on GY was therefore unreliable. Such cultivars confuse farmers as their performance is unpredictable temporally and spatially, and contributes to the low adoption of improved cultivars by farmers.

Sallah et al. (1997) found significant GE interaction effects for GY, days to mid silking (SD), plant height (PH), and number of ears per plant (EPP) under both high and low nitrogen. This means that GY, SD, PH and EPP may not be effective in selecting superior genotypes under both high and low soil fertility. Kling et al. (1997) reported that anthesis-silking interval (ASI) had significant genotype x nitrogen interaction effects under low N implying that its expression was influenced by environment, and information of ASI may only be effective in selecting superior genotypes under low fertility. Gallais and Coque (2005) reported significant genotype x N interaction effects for GY which were attributed to effects on kernel number. It implies that reducing kernel abortion could increase tolerance to low nitrogen and selection for reducing ASI and increasing EPP were also probable options for improving tolerance to low N.

Genotypes differ in their yield, because they differ in their relative allocation of resources to the expression of each trait within the biological system (Yan and Wallace, 1995). The allocation is influenced by the environment under which a genotype is grown. Therefore, successful cultivars are those whose relative allocation of resources best fit the target environment. Cultivars that are low yielding in farmers’ crop environments may lack alleles to enable them have high yields in these environments or the alleles may be of independent genetic systems.

The objective of this study was to investigate GY stability of nine popular maize cultivars under contrasting soil fertility levels across three sites from each of the three agro-ecological regions in Zambia. The hypothesis tested in the study was that widely grown maize cultivars are stable in performance across different fertility levels and environments in Zambia.

3.2 Materials and Methods

3.2.1 Experimental sites and Natural Regions

The study was carried out in Luangwa (Region I), Chilanga (Region II) and Masaiti (Region III), during the 2005/06 and 2006/07 seasons. Region I lies in the low lands and receives rainfall of up to 800mm per annum, over 80-120d, with about five 10d dry periods of less than 30mm occurring in an average season. Region II receives annually between 800-1000mm, over about 100-140d, with about three 10d dry periods of less than 30mm. Region III receives over 1000mm of rain, over 120-150d in a year, at a probability of 70% and does not experience drought (Bunyolo et al., 1997). The actual amount of rainfall received at the trial sites is show in Table 3.1. Soils in Luangwa are more fertile than those at Chilanga which are superior in fertility to those at Masaiti. (Bunyolo et al., 1997). Mean temperature during the growing season vary from 20-25, 23-25 and 16-25˚C in Regions I, II and III, respectively (Bunyolo et al., 1997). Genotypes were evaluated at six environments (ENVs) in the three districts. An environment was defined as season x location combination as follows:

a) LUA-1: Trial conducted at Luangwa during the 2005/06 season
b) LUA-2: Trial conducted at Luangwa during the 2006/07 season
c) CHI-1: Trial conducted at Chilanga during the 2005/06 season
d) CHI-2: Trial conducted at Chilanga during the 2006/07 season
e) MASA-1: Trial conducted at Masaiti during the 2005/06 season
f) MASA-2: Trial conducted at Masaiti during the 2006/07 season

Table 3.1: Location and amount of rainfall (mm) received at the trial sites during the study period

	Location of trial site			Rain season	
Trial site	Latitude (S)	Longitude (E)	Altitude (m)	2005/06	2006/07
Luangwa	15.10	30.18	373	865.8	562.0
Chilanga	15.55	26.26	1227	910.5	568.0
Masaiti	12.97	28.64	1270	1312.3	1179.7

Rainfall data was collected by a respective nearest office of the Meteorological Department

3.2.2 Fertiliser Treatments

The fertiliser treatments were as follows:

Treatment 1: Full recommendation of both basal and top dressing fertilisation was applied as 20kg N, 44kg P and 30kg K ha^{-1} at planting and the recommended amount of top dressing nitrogen fertiliser was applied 30d after planting at a rate of 92kg N ha^{-1}. This represented the optimum or full dosage fertility conditions. At application of fertiliser, its granules were covered with soil to avoid it being washed away by the rains.

Treatments 2 to 4 represented the sub-optimal conditions or reduced fertiliser dosage as follows:

Treatment 2: Recommended basal dressing fertilisation was applied as 20kg N, 44kg P and 30kg P ha^{-1}at planting and no additional N was applied for top dressing. Therefore there was a reduced dosage of N.

Treatment 3: Recommended top dressing fertiliser of 92kg N ha^{-1} was applied 30d after planting. No basal dressing was applied at planting, that is, no P and K were applied. This dosage represented farmers who only applied top dressing fertiliser to maize during cultivation.

Treatment 4 - Control: No fertiliser was applied throughout the crop growing cycle, that is, no N, P and K were added to the soils.

3.2.3 Germplasm

The germplasm included six varieties which were sampled from a database of registered cultivars, maintained by the Seed Control and Certification Institute (SCCI) in Zambia and three local landraces. Stratified sampling was applied to represent different variety types that are grown in each agro-ecological region. Consequently, three hybrids, three improved open pollinated varieties (OPVs) and three local landraces, comprising one recommended in each of the three agro-ecological regions, were selected for the study (Table 3.2). The GY potential and the maturity period of the three landraces had not been established, although they were popular with farmers. None of the landraces was used in breeding the released cultivars under test. These were bred using foreign germplasm.

Table 3.2: Maize cultivars evaluated during the study

Variety type	Designation	Area of adaptation (agro-ecological Region)	Reference Number	Major features
Hybrid	SC403	I	4	Yield potential: 6t ha^{-1} Maturity: 120-123d Grain colour: white Grain texture: Flint Cross: Three way cross Year of release in Zambia: 1999
Hybrid	MM603	II	6	Yield potential: 7t ha^{-1} Maturity: 135-145d Grain colour: white Grain texture: dent Cross: Three way cross Year of release in Zambia: 1984
Hybrid	MRI724	III	3	Yield potential: 13t ha^{-1} Maturity: 150d Grain colour: white Grain texture: dent Cross: Single cross Year of release in Zambia: 1998
OPV	MMV400	I	1	Yield potential:3.5t ha^{-1} Maturity: 110-120d Grain colour: white Grain texture: flint Year of release in Zambia: 1984
OPV	ZM521	II	9	Yield potential: 4.5t ha^{-1} Maturity: 125-135d Grain colour: white Grain texture: dent Year of release in Zambia: 2004
OPV	MMV600	III	8	Yield potential: 5t ha^{-1} Maturity: 145-155d Grain colour: white Grain texture: semi flint Year of release in Zambia: 1984
Landrace	Kazungula	I	5	Yield potential: Unknown Maturity: Unknown Grain colour: white Grain texture: Flint
Landrace	Gankata	II	2	Yield potential: Unknown Maturity: Unknown Grain colour: white Grain texture: Semi-flint
Landrace	Pandawe	III	7	Yield potential: Unknown Maturity: Unknown Grain colour: white Grain texture: Flint

3.2.4 Experimental design and management

The trials were laid out as a split-plot experiment in randomized complete block design with three replications for each ENV. Factors investigated included cultivar and fertilizer treatment. Of the two, cultivar was required to be measured with highest precision. Therefore, whole-plot was fertiliser treatment and sub-plot was cultivar. The plot size was two rows of 5m and 0.75m between rows, and two plants per hill spaced 0.5m within the row (22 plants per row; total 44 plants per entry). The established plant density was 53,000 plant per ha. The trials were maintained clean of weeds by hand weeding throughout the growing cycle. Two border rows and plants at two hills at either end of the plot were excluded from data collected. The amount of rainfall received at each ENV is shown in Table 3.1. Initial soil fertility at each trial (Table 3.3) during the research was determined by the Zambia Agriculture Research Institute (ZARI) based on Woode (1988). Drought was severe and rainfall distribution poor at the hot ENVs LUA-1 and LUA-2 where much of the grain filling period was under drought.

Table 3.3: Soil analytical results at six environments

ENV	Depth (cm)	Hand (Text)	pH ($CaCl_2$)	Org (C%)	N (%)	P (Ppm)	K (me%)	Ca (me%)	Mg (Me%)
LUA-1	20	SCL	7.4	0.95	0.07	55	0.87	66.2	3.6
LUA-1	40	SCL	7.0	0.70	0.05	57	0.87	26.2	3.6
CHI-1	20	SCL	8.0	1.07	0.08	6	0.85	32.0	9.8
CHI-1	40	SCL	7.9	0.89	0.06	5	0.37	25.0	5.3
MASA-1	20	SCL	5.3	0.84	0.06	11	0.44	4.1	2.6
MASA-1	40	SCL	4.7	0.79	0.06	7	0.31	3.6	2.1
LUA-2	20	SCL	7.6	0.44	0.03	96	0.97	16.7	1.5
LUA-2	40	SCL	7.7	0.37	0.02	84	0.77	16.2	1.0
CHI-2	20	SCL	6.9	2.13	0.15	18	0.77	11.6	0.5
CHI-2	40	SCL	6.4	0.33	0.02	3	0.61	31.0	1.0

*MAS-2 soil analysis results are not available

Key for soil texture: S = Sand, LS=Loamy Sand, SL= Sandy Loam, SC= Sandy Clay, SCL= Sandy Clay Loam

Key for soil pH_2: < 4.0 = Extremely acid, 5.0-4.0 = Strongly acid, 5.0-7.0 Medium acid, 7.0=Neutral, >7.0 Alkaline.

3.2.5 Measurement of characteristics

Anthesis date (AD) and silking date (SD) were obtained as ‘number of days after planting’, when 50% of plants were shedding pollen and silking, respectively. The ASI was calculated as SD-AD. Leaf rolling (Lroll) was measured by scoring on a scale from zero (unrolled, turgid leaves, desirable) to one (severely rolled leaves, undesirable), while leaf senescence (Lsene) was measured during grain filling by estimating the fraction of area, which had turned brown (dead leaf). Tassel size (Tsize) was determined by counting number the number of primary branches of the tassel per plant (ten plants per plot). Plant height (PH) was measured as height between the base of a plant to the insertion of the first tassel branch of the same plant. At harvest, the two border rows and plants at two hills at either end of the plot were excluded from the harvest (whole plot). Number of ears (defined as having at least one fully developed grain) expressed as a fraction of number of plants at harvest, was used to determine the number of ears per plant (EPP). Grain yield was measured as weight of shelled grains (tonnes per hectare) adjusted to 12.5% grain moisture. Grain moisture was measured using an electronic moisture meter used also by Seed Control and Certification Institute. Grain texture was measured on a scale from 0 to 1 as follows; kernel of deep depression (fully dent) = 0, medium depression = 0.25, mild depression = 0.5, roughly smooth = 0.75, smooth (fully flint) = 1.0.

3.2.6 Data analysis

A combined analysis across the environments was considered and homogeneity of variances under the six environments was determined using respective mean square error (MSE) of the sub-plot (Error b). The ratio of MSE_{large} to MSE_{small} (F-max test) was 8. Therefore, the results of all the ENV could not be combined. According to Mead et al. (2003) when ratio of MSE_{large} to MSE_{small} was above 4, combined analysis was not effective. However, a combined analysis was done for ENVs whose ratio for MSE_{large} to MSE_{small} allowed the analysis. Therefore, results of site and combined analysis are presented.

Data were analyzed as a split-plot across four environments in SAS as described by Steel and Torrie (1980). ENV and their interactions with fertilisation and cultivar were considered random while fertilisation and cultivar were fixed. Combined means (y) were calculated as;

$$y= \mu + R_i + A_j + Є_a + B_k + AB_{jk} + Є_b + C + Є_c + CA + Є_d + CB + ABC + Є_e$$

R= Block effects:1, 2, 3.

A = Fertiliser treatment effects: k = 1, 2, 3, 4.

B = Cultivar effects: l = 1, 2, 3 …, 9.

C = Environment effects: 1, 2, 3, 4

$Є_a – Є_e$ = Random errors as follows:

$Є_a$ = Error a.

$Є_b$ = Error b

$Є_c$ = Error c

$Є_d$ = Error d

$Є_e$ = Error e.

Phenotypic correlations of various traits were also calculated. Relative yield reduction was defined as GY reduction due to stress (Fertilisation 4) in comparison to that under optimal conditions (Fertilisation 1) and was calculated as: $(1 – GY_{NF}/GY_{OP}) \times 100\%$ where: GY_{NF} = is grain yield under stress environment and GY_{OP} = is grain yield under optimal environment (non stress). Main effects of the factors and their interactions were analyzed in terms of their importance in influencing GY. Crossover type of interaction effects for GY were assessed where the interaction effects were significant.

3.3 Results

3.3.1 Cultivar environment interaction effects of maize varieties under different fertilisation in the three agro-ecological regions

The results showed that fertilisation x cultivar interaction effects were significant at CHI-1 ($P \leq 0.05$), MASA-1, and CHI-2 ($P \leq 0.10$) (Table 3.4a). At $P \leq 0.05$, cultivars were significantly different at all the six ENVs except at LUA-1 where they were significant at $P \leq 0.10$. Fertilisation was significant ($P \leq 0.05$) at CHI-1, CHI-2, MASA-1 and MASA-2 but was only significant at $P \leq 0.10$ at LUA-1 and LUA-2.

Table 3.4a: Analysis of variance for GY for nine cultivars under four fertiliser levels at six environments

		Mean Squares					
Source of variation	d.f.	LUA-1	LUA-2	CHI-1	CHI-2	MASA-1	MASA-2
Block stratum	2	0.666	0.485	0.609	6.612	4.610	0.609
Fertilisation	3	37.039**	3.373**	50.725*	6.935*	41.494*	105.618*
Residual	6	9.668	0.902	1.044	0.727	1.051	4.025
Genotype	8	2.809**	0.507*	2.906*	8.126*	6.699*	5.234*
Fertilisation x Genotype	24	1.979	0.220	2.223*	2.570**	1.210*	1.444
Residual	64	1.509	0.213	1.014	1.644	0.578	1.296
Total	107						

* denotes significant at $p \leq 0.05$, ** denotes significant at $p \leq 0.10$.

Note: The degrees of freedom for residual was 59 and 45 at MASA-2 and LUA-2 Envs, respectively as a result of missing values.

A combined analysis of trials at ENVs LUA-1, CHI-1, CHI-2 and MASA-1 revealed that main effects of Fertilisation, Cultivars and ENVs and their interactions were all significant ($P \leq 0.05$) for GY, AD, SD, ASI and PH (Table 3.4b).

Table 3.4b: Analysis of variance for GY for nine cultivars under four fertiliser levels at four environments

		Mean squares				
Source	df	GY	AD	SD	ASI	PH
Rep	2	1.153	43.863*	39.668*	17.381*	1729.476*
Fertilizer	3	51.202*	263.422*	332.574*	51.873*	18317.920*
Fertiliser x Rep – Error a	6	3.790	6.302	17.558	8.289	611.469
Variety	8	8.447*	136.846*	132.752*	6.911*	6348.531*
Fertiliser x Variety	24	2.132*	5.071*	6.984*	6.791*	405.694*
Rep x Variety (Fertiliser) – Error b	64	3.090	6.700	6.672	4.510	315.450
ENV	3	307.093*	2254.688*	1274.043*	210.120*	112788.800*
ENV x Rep– Error c	6	1.021	7.372	18.444	21.626	386.762
ENV x Fertiliser	9	42.914*	164.485*	262.300*	33.006*	11988.800*
ENV x Fertiliser x Rep– Error d	18	4.016	4.115	7.460	8.784	1078.769
ENV x Variety	24	4.289*	28.017*	29.620*	5.903*	995.249*
ENV x Fertiliser x Variety	72	2.836*	9.075*	9.673*	5.820*	433.828*
ENV x Rep x Variety (Fertiliser) – Error e	192	3.238	5.326	5.976	4.870	297.986

* denotes significant at $p \leq 0.05$,

3.3.2 Grain yield of cultivars under different fertiliser levels at six ENVs

Cultivars achieved highest GY at CHI-1 and lowest at LUA-1. The grand mean of GY, was 3.95t ha^{-1} at CHI-1 and 0.310t ha^{-1} at LUA-1. Under contrasting fertiliser treatments, cultivars achieved highest yields under Fertilisation 1 (full fertilisation), followed by Fertilisation 3 (top only), 2 (basal only), and 4 (nil fertilisation). Grain yield ranged from 5.280t ha^{-1} at MASA-2 under full fertiliser treatment, to 0.022t ha^{-1} under top dressing only, at LUA-1 (Table 3.5).

Table 3.5: Environment means of GY (t ha^{-1}) under different fertilizer treatments

	Fertiliser treatment				
Environment	Basal + top	Basal only	Top only	None	SE
LUA-1	0.333	0.070	0.022	0.813	± 0.113
CHI-1	5.079	3.398	3.428	1.721	± 0.197
CHI-2	3.330	3.780	4.510	4.160	± 0.164
MASA-2	5.280	1.870	1.660	0.780	± 0.386
Mean	3.506	2.280	2.405	1.869	

LSD = 0.651, $p \leq 0.05$

Considering the highest yielding cultivar between the ENVs it was found that on average, GY in Luangwa was only 13% of that at Chilanga and 22% of that at Masaiti. At Masaiti cultivars achieved 73% of the GY obtained at Chilanga. However, under zero fertilisation GY at Luangwa was 20% of that at Chilanga, and 42% of GY at Masaiti. Grain yield at Masaiti ranged between 61-93% of that at Chilanga over the environments.

The mean grain yield showed that the yield advantage of applying fertiliser was 99%, 24%, and 41% when fully recommended fertilisation, basal dressing only and top dressing only were applied, respectively. At LUA-1, the highest yielder was MRI724 which achieved 0.57t ha^{-1} while the lowest at the sites was MMV400, which achieved 0.2t ha^{-1} (Table 3.6). At Chilanga (CHI-1 and CHI-2), highest in GY was SC403 (4.82t ha^{-1}) while the lowest was ZM521 that achieved 2.62t ha^{-1}. Pandawe yielded highest at Masaiti (MASA-2) and achieved 3.20t ha^{-1}, while ZM521 was lowest with 1.34t ha^{-1}.

Table 3.6: Grain yields (t ha^{-1}) of cultivars under the different environment

Cultivars	LUA-1	CHI-1	CHI-2	MASA-2
SC403	0.22	3.12	4.82	1.83
MM603	0.33	3.04	4.08	3.02
MRI724	0.57	4.24	4.76	2.64
MMV400	0.20	3.18	2.70	1.67
ZM521	0.29	4.14	2.62	1.34
MMV600	0.15	2.98	4.05	2.28
Kazungula	0.40	2.96	4.61	2.55
Gankata	0.36	3.64	3.63	3.04
Pandawe	0.27	3.37	4.25	3.20
Statistics				
Mean	0.31	3.41	3.95	2.40
SE	± 0.32	± 0.82	± 1.01	± 0.73

LSD = 0.481, $p \leq 0.05$

Hybrids and landraces were generally superior to OPVs in GY at all ENVs. MRI724 was highest yielder at LUA-1 but was not significantly superior to any of the cultivars. At CHI-1724 and ZM521 were first and second in GY respectively and were both significantly different to all other cultivars but not between them (Table 3.7). The hybrid was second to SC403 at CHI-2 and was forth at MASA-2, where Pandawe and Gankata were first and second highest yielding cultivars, respectively. Gankata ranked third at LUA-1 and CHI-1. Kazungula that originates in Region I, ranked second at LUA-1 and 3rd at CHI-1.

Table 3.7: Ranking of varieties for GY in each ENV, averaged over fertility levels

Rank	LUA-1	CHI-1	CHI-2	MASA-2
1	MRI724	MRI724	SC403	Pandawe
2	Kazungula	ZM521	MRI724	Gankata
3	Gankata	Gankata	Kazungula	MM603
4	MM603	Pandawe	Pandawe	MRI724
5	ZM521	MMV400	MM603	Kazungula
6	Pandawe	SC403	MMV600	MMV600
7	SC403	MM603	Gankata	SC403
8	MMV400	MMV600	MMV400	MMV400
9	MMV600	Kazungula	ZM521	ZM521

Note: Hybrids were MM603, MRI724, and SC403 while OPVs included MMV400, MMV600 and ZM521. Landraces included Gankata, Kazungula, and Pandawe.

Based on average GY across all the six ENV (individual site analysis), the three highest yielding cultivars under full fertilisation were Gankata, MRI724 and Kazungula while under basal only, it was MRI724, Gankata and SC403. MRI724, Kazungula and MMV600 were highest yielders under top only, while MRI724, Kazungula and Gankata were highest in GY under nil fertilisation across ENVs. MMV400 was the lowest yielding under full and nil fertiliser treatments, while MMV600 and ZM521 were lowest under basal dressing only and top dressing only fertiliser treatments (Table 3.8).

Table 3.8: Grain yields (t ha^{-1}) of cultivars under different fertiliser treatments and ENVs

	Cultivars reference number								
	1	2	3	4	5	6	7	8	9
ENV	*Full fertiliser treatment*								
MASA-1	3.35	6.96	7.07	4.99	5.72	3.98	3.79	3.39	4.65
MASA-2	3.87	5.21	4.80	5.45	6.63	6.02	6.79	4.35	4.36
CHI-1	3.53	5.91	5.51	4.50	4.94	5.29	4.58	3.91	7.55
CHI-2	2.20	4.50	4.28	3.17	2.94	4.10	3.25	4.01	1.55
LUA-1	0.21	0.18	0.40	0.34	0.44	0.37	0.50	0.31	0.24
LUA-2	0.31	0.26	0.69	0.25	1.08	0.55	0.43	0.50	0.08
Mean	2.24	3.84	3.79	3.12	3.63	3.38	3.22	2.74	3.07

Table 3.8: Grain yields (t ha^{-1}) of cultivars under different fertiliser treatments and ENVs contd.

	Cultivars reference number								
	1	2	3	4	5	6	7	8	9
ENV	*Basal dressing only*								
MASA-1	2.15	3.10	4.17	2.54	2.16	2.97	2.46	2.24	2.70
MASA-2	0.93	2.98	2.65	1.49	1.86	2.38	1.83	1.71	1.03
CHI-1	3.29	5.02	4.75	3.24	2.05	2.28	3.41	2.44	4.11
CHI-2	2.01	2.86	5.36	5.42	5.18	4.62	4.65	2.03	1.89
LUA-1	0.04	0.03	0.05	0.15	0.08	0.01	0.11	0.09	0.07
LUA-2	0.17	0.12	0.22	0.29	0.05	0.35	0.16	0.19	0.06
Mean	1.43	2.35	2.87	2.19	1.90	2.10	2.10	1.45	1.64
	Top dressing only								
MASA-1	2.39	2.75	4.61	2.80	2.86	3.81	3.52	2.36	3.02
MASA-2	1.33	2.68	2.42	0.00	1.16	2.84	2.87	2.09	0.00
CHI-1	4.18	2.87	3.99	2.83	2.82	2.96	4.16	3.87	3.17
CHI-2	3.82	2.78	5.74	5.73	5.45	3.47	4.54	5.70	3.39
LUA-1	0.00	0.00	0.05	0.08	0.04	0.00	0.01	0.00	0.02
LUA-2	0.52	0.61	2.01	0.73	0.90	1.47	1.06	0.86	0.67
Mean	2.04	1.95	3.14	2.01	2.21	2.42	2.69	2.48	1.66
	Nil fertiliser treatment								
MASA-1	1.55	2.79	2.98	1.26	1.39	2.56	1.82	1.32	1.87
MASA-2	0.55	1.29	0.70	0.47	0.55	0.82	1.29	1.00	0.31
CHI-1	1.70	0.75	2.71	1.92	2.05	1.64	1.31	1.68	1.73
CHI-2	2.77	4.37	3.67	4.97	4.85	4.14	4.57	4.45	3.65
LUA-1	0.54	1.23	1.79	0.30	1.05	0.95	0.44	0.2	0.82
LUA-2	0.35	0.18	0.37	0.36	0.87	0.23	0.00	0.29	0.09
Mean	1.24	1.77	2.03	1.55	1.79	1.72	1.57	1.49	1.41

Note for cultivar reference number: 1 = MMV400, 2 = Gankata, 3 = MRI724, 4 = SC403, 5 = Kazungula, 6 = MM603, 7 = Pandawe, 8 = MMV600, 9 = ZM521.

A combined analysis of four ENVs found Gankata highest in GY (3.27t ha^{-1}) over all other cultivars. However, the superiority was not significant to MRI724, Kazungula, MM603 and Pandawe (Table 3.9). Gankata was also tallest and was seconded to Pandawe. The earliest cultivar was MMV400 (AD = 64.69) while the most late maturing was MRI724 (AD = 70.10). Variation of the cultivars in ASI was close. MM603 had the largest tassels but its size was not significantly different from Gankata, Kazungula and Pandawe.

Table 3.9: Performance of genotypes in various traits at LUA-1, CHI-1, CHI-2, MASA-2 across different fertiliser treatments and ENVs

	Cultivar reference number									
Trait	1	2	3	4	5	6	7	8	9	LSD ($p \leq 0.05$)
GY(t ha^{-1})	1.94	3.27	3.08	2.52	2.63	2.62	2.77	2.39	2.14	0.72
AD (cm)	64.69	69.62	70.10	66.50	68.88	68.65	68.92	67.56	67.44	1.06
SD (days)	68.12	72.81	73.12	69.88	72.69	72.79	72.31	71.21	71.48	1.05
ASI (days)	3.44	3.19	3.02	3.38	3.81	4.15	3.40	3.65	4.04	0.87
PH (cm)	142.60	176.58	159.60	160.92	161.56	164.09	172.33	155.70	142.93	7.24
EPP	0.84	0.84	0.99	0.91	0.87	0.84	0.98	0.84	0.87	0.12
Gtext	0.74	0.40	0.76	0.53	0.47	0.45	0.43	0.60	0.65	0.22
Lroll	0.12	0.00	0.00	0.00	0.10	0.00	0.04	0.08	0.12	0.11
Lsene	0.16	0.1091	0.12	0.11	0.13	0.11	0.12	0.14	0.11	0.08
Tsize (cm)	12.8	14.14	10.61	12.25	13.89	14.63	13.78	12.93	12.54	1.11

Note for cultivar reference number: 1 = MMV400, 2 = Gankata, 3 = MRI724, 4 = SC403, 5 = Kazungula, 6 = MM603, 7 = Pandawe, 8 = MMV600, 9 = ZM521.

3.3.3 Tolerance to low soil fertility of the maize cultivars

The relative yield reduction under nil fertilisation in comparison to GY under full fertilisation was lowest (least reduction) at Luangwa (LUA-1), and was highest at Masaiti (MASA-2). The top three cultivars for relative yield reduction were Gankata, ZM521 and MRI724 (in that order). The cultivars with the least relative yield reduction were Pandawe and MMV 600 (Table 3.10). Cultivars achieved higher GY under nil fertilisation than under full fertilisation at LUA-1, LUA-2 and CHI-2, where Gankata increased GY by about 6 times (LUA-1) of the GY under full fertilisation. MRI724 was the second to Gankata in most tolerant cultivar to low soil fertility based on relative yield reduction.

In Luangwa the top three cultivars in relative yield reduction were Gankata, MRI724 and ZM521 while at Chilanga ZM521, SC403 and Pandawe had the lowest yield reduction. At Masaiti the top three in relative yield reduction were MM603, MMV400 and Pandawe.

Table 3.10: Relative yield reduction (%) of the maize cultivars

	Cultivar reference number								
ENV	1	2	3	4	5	6	7	8	9
MASA-1	54	60	58	75	76	36	51.9	61	60
MASA-2	86	75	85	91	92	86	81	77	93
CHI-1	52	87	51	57	58	69	71	57	77.1
CHI-2	-26	2.9	14	-57	-65	-1	-41	-11	-135
LUA-1	-155	-593	-349	11	-137	-154	13	37	-248
LUA-2	-15	31	47	-44	20	58	104	41	-8
Mean	-0.8	-56	-16	22	7.3	15.7	46.8	43.6	-27

Note for cultivar reference number: 1 = MMV400, 2 = Gankata, 3 = MRI724, 4 = SC403, 5 = Kazungula, 6 = MM603, 7 = Pandawe, 8 = MMV600, 9 = ZM521.

3.3.4 Correlation of grain yield with selected secondary traits

Correlations were calculated using cultivar means under each fertiliser level at each site and using cultivar site means across the four fertiliser levels. Correlation (r) of grain yield (GY) with secondary traits in the highest yielding ENV (MASA-2) was compared to correlations of traits with GY at CHI-2, where cultivars had highest yields under nil fertilisation (Table 3.11).

Table 3.11: Correlation of GY with secondary traits under full and nil fertilisation at MASA-2 and CHI-2

	MASA-2			CHI-2		
Trait	Across	Full	Nil	Across	Full	Nil
ASI	-0.159	0.258	-0.230	0.010	0.318	0.121
EPP	0.097	0.153	0.181	0.104	0.203	0.080
Gtext	-0.550*	-0.291	-0.490*	0.051	-0.028	-0.214
Lsene	-0.350*	0.017	-0.106	0.032	0.091	0.029
Tsize	0.395*	0.058	0.205	-0.174	0.046	0.037

At Masaiti, GY had significant ($p \leq 0.05$) correlation with grain texture Gtext (r = -0.55*), Lsene (r = -0.35*) and Tsize (r = 0.395*) across fertiliser treatments. However, the correlation of GY with secondary traits across fertiliser treatments was non-significant ($p \leq 0.05$) at Chilanga. The correlation of GY secondary traits was non-significant ($p \leq 0.05$) under full fertilisation at both MASA-2 and CHI-2. Only Gtext at MASA-2 had significant ($p \leq 0.05$) correlation with GY under nil fertiliser treatment, while none of the traits had a significant ($p \leq 0.05$) correlation with GY at CHI-2 under the fertiliser treatments.

3.4 Discussion

3.4.1 Grain yield under different fertiliser levels

Hybrids and landraces dominated in GY at the six environments and across the different fertility levels. However, due to farmers' financial limitations, landraces would be preferred. This was in agreement with findings by CSO (2005) that most small-scale farmers in Zambia produced maize from their local landraces. Superiority of some landraces over some improved cultivars meant that some varieties that were not superior under the local cropping system of farmers were released. This suggests that the variety evaluation system failed to identify varieties that were appropriate to the cropping system of small-scale farmers. Silwimba and Miti (2005) found that only about a third of the released maize varieties were being actively grown. This implies that evaluation of varieties under high fertility conditions only is inappropriate when, upon release most farmers cultivate the varieties under low fertility conditions as is the case in Zambia.

The fact that maize cultivars yielded highest under Fertilisation 1 (full fertilisation) followed by Fertilisation 3 (top dressing only), 2 (basal dressing only) and 4 (no fertilisation) suggested that, where fertiliser is limited the option of applying top dressing only was more effective than that of applying basal dressing. It also meant that nitrogen was more limiting than were other essential elements (potassium and phosphorous) applied. This is confirmed by the low amount of initial N at trial sites (Table 3.3). The high ranking of MRI724 across all the test environments could have meant that this hybrid exhibited static stability for GY across the environments. The results on stability were in agreement with Fox et al. (1997). However, at Luangwa MRI724 yielded 12-19% of its GY at Chilanga and 12-31% of its GY at Masaiti. On average GY achieved by cultivars at Luangwa was 13% and 22% of GY achieved at Chilanga and Masaiti, respectively. Grain yield at Masaiti ranged between 61-93% of that at Chilanga over the environments. Tollenaar and Lee (2002) reported that static stability is exhibited when a cultivar maintains its GY under changing environmental conditions. This means that all the cultivars lacked static stability for GY across environments, but exhibited dynamic stability as they responded to change of environment.

The superiority of MRI724 across test environments suggests that hybrids were also a possible solution for cultivation of maize under low input conditions. Possibly, one or both parents of MRI724 had an inherent ability to tolerate low soil fertility and the different rainfall pattern across the three agro-ecological regions. This is confirmed by its low ASI, leaf rolling and leaf sencence (Table 3.9). Tolerance to low soil fertility may have been also due to heterosis. However, MRI724 is a privately owned variety and access to information on its parentage was limited. Considering that most small-scale farmers plant landraces, the high ranking of MRI724 under varying crop fertilisation levels suggests that prior promotion of the hybrid among the small-scale farmers in rural areas was low. However, the yield gap between MRI724 and the best landrace, Gankata was not always large, suggesting that farmers might prefer the landrace when resources for seed were limiting.

On average, the advantage of applying fertiliser was 99%, 24%, and 41% under recommended, basal only and top only fertiliser treatments, respectively. The cultivars generally responded positively to fertilisation at the ENVs except at LUA-1 and Lua-2 where the drought was severe and could have limited the plants to utilise the fertiliser. The cultivars exhibited dynamic (agronomic) stability meaning that the environment influenced the GY achieved by a cultivar (Romagosa and Fox et. 1993; Tollernaar and Lee, 2002). These results also implied that at CHI-1, CHI-2, MASA-1 and MASA-2, farmers will double their yields irrespective of type of cultivar if they used recommended fertilisation and will increase yields by about half if only top dressing fertiliser was applied. This means that measures that increase farmer access to fertiliser, such as subsidies (though not sustainable but effective in short term), infrastructure and roads will significantly increase maize production in CHI (Region II) and MASA (Region III). The results showed that nitrogen as a top dressing fertiliser was a critical input and inability to top dress maize among the majority of resource poor farmers Region II and Region III, is a limiting factor. Cost effective measures such as developing varieties that tolerate low N stress also offer a partial solution to the problem.

Based on average rank of GY across ENVs and fertilizer treatments, cultivar yields were highest for MRI724, Gankata, MM603, Kazungula, Pandawe, SC403, ZM521, MMV600 and MMV400 (in that order). All of the three local landraces performed well across all fertilisation levels as did MRI724 implying that they possessed alleles for tolerance to the effects of differences in fertilisation levels. Azar et al. (1997) found variation in GY, grain colour and grain texture in landraces. Lafitte et al. (1997) reported that landraces exhibited superiority over improved varieties in grain N concentration suggesting that they were superior in accumulating N. Gankata was superior in accumulation and use of N to all OPVs, landraces, and hybrids except for MRI724. Superiority of landraces over improved varieties likely motivated farmers into planting them and poses a challenge to plant breeders to develop varieties that out-yield such landraces under farmer conditions. All the improved cultivars were bred using foreign germplasm could be facing challenges to local adaptation. Therefore, the superior landrace could be used as germplasm in breeding cultivars targeting similar environments in the country. Improvement of such a landrace per se is also warranted.

3.4.2 Cultivar x environment interaction effects

Information on interaction effects of the cultivars with the test environments is important in explaining the performance of cultivars. Cultivars x fertilisation interaction effects were significant for GY at CH1-1, MASA-1 ($p \leq 0.05$) and CHI-2 ($p \leq 0.10$). This implied that GY achieved by the cultivars were differently affected by N levels at the different ENVs. However, the cultivars did not exhibit crossover type of interaction effects, implying that the highest yielding cultivar was superior in the respective ENVs that best fit it. Therefore, MRI724 was the best at CHI-1 and MASA-1 while SC403 was the best at CHI-2.

A combined analysis for trials carried out LUA-1, CHI-1, CHI-2 and MASA-1 found that Fertilisation, Cultivars and ENVs, and their interactions were all significant ($P \leq 0.05$) for GY, AD, SD, ASI and PH (Table 3.4b). This implied that cultivars performed differently at the ENvs and across contrasting fertility regime. Therefore, the cultivars could be discrimated and superior ones identified.

The cultivars generally, achieved higher yields where more fertiliser (especially nitrogen) was applied (agronomic stability). Therefore, cultivation of the cultivars under low soil fertility in these areas will generally result in low yields. Where farmers are unable to access fertilizer, soil enriching practices such as crop rotation (especially with legumes) and growing of appropriate cover crops should be encouraged.

Cultivar x fertilisation interaction effects for GY, were not significant at MASA-2, LUA-1 and LUA-2 ($p \leq 0.05$). At these ENVs, the relative GY of cultivars are not affected by fertility environment. This means the highest yielding cultivars across fertilisation level at the three ENVs based on average rank of GY (MRI724 and Kazungula) were superior in all the three ENVs. The non-significant cultivar x fertilisation interaction effects at the ENVs could have been due to water deficiency at LUA-1 and LUA-2 that could have limited genetic expression. Both LUA-1 and LUA-2 are located in Region I which experiences drought of about 50d during a growing season of about 80-120d. During the 2006/07 season MASA-2 received about double the amount of rainfall (Table 3.1) received at LUA-2. The heavy rainfall could have drained some fertiliser, especially nitrogen, because planting and top dressing were followed by the rains. This could have limited the genotypic expression at MASA-2.

When GE is not significant, discussion of differences in performance of cultivars is concentrated on main effects but, if significant it should be determined if the GE is associated with crossover effects (Romagosa and Fox, 1993; Fox et al., 1997). Crossover type of GE is the most important in plant breeding. It occurs when there are changes in ranking of cultivars across environments. When GE is of non-crossover type, superior cultivars may be recommended for all the environments. These results have shown that cultivar x fertilisation level were important for GY at CHI-1, CHI-2 and MASA-1. The type of GE interaction effects for GY were of the crossover type for all cultivars. Therefore, a cultivar should be recommended to a specific fertilisation level at an ENV that best fits it. MRI724 best fitted all fertilisation level at MASA-1 but did not best fit all the fertilisation level at the other ENVs. This means that high yielding cultivars under a specific fertilization level be sought at each ENV.

Sallah et al. (1997) found significant GE interaction effects for GY, mid silking, plant height, and EPP under both high and low N implying that N level influenced genotypic expression. This means that cultivars be sought that perform best under a defined N fertilisation level. Gallais and Coque (2005) observed that many studies showed significant cultivar x N interaction effects for GY. They attributed this to cultivar x N interaction effects for kernel number and concluded that reducing kernel abortion just after fertilisation increased tolerance to low N. Selection for reduced ASI and reduced barrenness are probable options for this.

3.4.3 Tolerance to low soil fertility of the maize cultivars

Relative yield reduction was used to identify superior cultivars to low soil fertility under the no fertiliser treatment. Lower values indicated tolerance to low soil fertility (Rosielle and Hamblin, 1981). The lowest relative yield reduction was expressed by cultivars at Luangwa implying that drought at LUA-1 and LUA-2 could have played a major role in cultivars failing to use the nutrients. Probably moisture was not adequate to dissolve the nutrients which have affected its uptake. The fertilizer could have also attempted to draw moisture from the plants while dissolving, thereby physiologically weakening them. The top three genotypes in relative yield reduction were Gankata, ZM521 and MRI724 (in that order) while, Pandawe, and MMV600 had the greatest yield reduction. Area of adaptation for both Pandawe and MMV600 is Region III (high rainfall area), suggesting that the cultivars had adaptive traits for high rainfall, hence their low GY potential in the dry Region I.

These results showed that high maize yield potential of the cultivars achieved at research station was difficult to attain by an average farmer in Zambia. Drought and low soil fertility limit the cultivars from performing to expectation. Information on expected cultivar yield based on on-farm trials should be provided to farmers too. Remaining silent on this and on practices required for farmers to achieve the potential yield, will continue to disappoint farmers and may draw them away from planting improved seeds. Provision of cultivars that tolerate these abiotic stresses should be prioritized.

A well planned breeding strategy involving precise identification and measurement of appropriate traits, and selection of superior cultivars could enhance further the GY of varieties developed for low soil fertility environments. Local landraces should be used as germplasm in developing such varieties, as they probably have inherent adaptability to the local environment. This is supported by superiority in GY and relative grain yield under stress by Gankata and Kazungula. These results showed that the landraces were generally tall and with large tassels. Increasing yield as a result of reduction in this traits should form part of a breeding strategy that uses the same as germplasm.

3.4.4 Correlation of grain yield with selected secondary traits

The importance of a secondary trait in selecting superior cultivars depended on its correlation with GY. It was found that GY correlated significantly with Gtext, Lsene and Tsize ($p \leq 0.5$) across fertilisations at MASA-2 and not under full or nil fertilisation. This implied that their information was not useful to identify high yielding cultivars targeting the nil fertilisation farming environment prevalent under most small-scale maize cultivation. However, the correlation of grain yield with Gtext was significant under nil fertilization at MASA-2 ($r = -0.49^*$). Grain yield increased as Gtext (flintiness) reduces implying that farmer selection based on increasing flintiness selected for low GY. These results also suggest farmer selection of Gtext could have been based on improving grain quality which were also said to be important (Chapter 2). The relationship between flintiness and low GY could also be due to environmental causes as stressed plants may produce small and flint kernels. Although, these results imply that Gtext could be used to identify superior cultivars under low soil fertility, only three landraces were used in the trial and further research on the same is required.

3.5 Conclusions and Implications to variety development and evaluation for release

The study has found that cultivar x fertiliser interaction effects for GY were important at CHI-1, CHI-2 and MASA-1. However, the cultivars did not exhibit crossover type of interaction effects, implying that the highest yielding cultivar was superior under ENVs that best fit it. Therefore, MRI724 was superior at CHI-1 and MASA-1, while SC403 was superior at CHI-2. Cultivar x fertiliser interaction effects for GY were not significant ($p \leq 0.10$) at LUA-1, LUA-2 and MASA-2 implying that the best cultivar across these ENVs should be cultivated under all the ENVs. It has also been found that the cultivars lacked static stability and positively responded to fertilisation. Fertiliser application to maize was found detrimental under the hot and low rainfall environments at LUA-1 and LUA-2 where cultivars yielded higher under nil fertilisation than where fertiliser was applied. It is recommended that appropriate type and rate of fertiliser application be researched on and recommended to such areas. At other ENVs cultivars generally achieved high GY under high input (full fertilisation) and low GY under nil fertilisation. The three highest yielding cultivars under the four fertiliser treatments were as follows:

Basal + top dressing	Basal dressing only	Top dressing only	Nil fertilisation
Gankata	MRI724	MRI724	MRI724
MRI724	Gankata	Gankata	Kazungula
Kazungula	SC403	MMV600	Gankata

Based on average rank of GY across ENVs and fertilizer treatments, the highest yielding cultivars were MRI724, Gankata, MM603, Kazungula, Pandawe, SC403, ZM521, MMV600 and MMV400 (in that order). Superiority of landraces to all OPVs and two hybrids challenges plant breeders to develop high yielding varieties under low input conditions under which the majority of farmers cultivate maize in Zambia. It also calls for the seed certification system to evaluate candidate varieties for performance under low inputs as well, to simulate the farmers' environment. This should begin with defining farming practices and all candidate varieties should be tested under such environments. Popular landraces should also be included in such trials as checks for performance.

The advantage of applying fertiliser was 99%, 24%, and 41% for recommended fertilisation, basal dressing only and top dressing only, respectively. This meant that farmers would almost double their yields, irrespective of type of cultivar, if they used recommended fertilisation practices and they would increase yields by about half if only top dressing fertiliser was applied. Therefore, measures that increase farmer access to fertiliser in Zambia, such as subsidies, infrastructure and roads will increase maize production. The results also showed that where resources were limiting, application of top dressing nitrogen fertiliser yields higher than basal dressing fertiliser. Provision of varieties that tolerated low soil fertility such as nitrogen offered a cost effective partial solution to the problem.

Local landraces which were found to be superior in GY and in tolerance to no fertilisation could be recommended as a good source of germplasm for developing varieties targeting environments of low soil fertility in Zambia. Superiority of landraces over improved varieties suggests that the variety release system should be strengthened. The study has found that variety assessment exclusively under high input is inappropriate for Zambia where most farmers cultivate maize under low input. It is recommended that candidate varieties should be evaluated under conditions that resemble the farmer crop environment including under low soil fertility.

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Chapter 4: S_1 Selection of local maize landraces for low nitrogen tolerance

Abstract

Low soil nitrogen (N) is one of the most limiting factors to maize production in Zambia. In this study S_1 selection was used to select for tolerance to low N within local landraces during 2004-2007 in Zambia. Ninety-six maize landraces were evaluated under low N, drought and optimal conditions. At the same time, the landraces were selfed in a nursery, under optimal conditions to generate S_1 lines. Data on grain yield (GY), number of ears per plant (EPP), leaf senescence (Lsene) and anthesis-silking interval (ASI) were used to calculate selection indices. Fourteen S_1 lines, from each of the best four landraces under low N, drought, optimal and across these environments were selected for evaluation, under low N, drought and optimal conditions as well as crossing them to a single cross hybrid tester. Twenty-two best performing S_1 lines under low N, drought, optimal and across the three selection environments were identified and their respective testcrosses selected for evaluation under the three selection environments. General combining ability (GCA), broad sense heritability (H^2), and genetic correlations (r_G), were calculated. Positive significant GCA effects for GY under low N were found suggesting that population improvement under this stress could be effective. Heritability for GY under low N conditions was low (0.38) implying that selection based on GY under low N would not be effective. The r_G for GY under low N and optimal environments was moderate (0.458) suggesting that genotypes selected for GY in one environment may only be moderately effective in the other. Grain yield correlated with EPP (r = 0.551*), Lsene (r=0.199*) and with tassel size (r = 0.210*). Therefore, selection for GY, EPP, Lsene and tassel size could be effective under low N stress. Landraces LR76, LR84 and LR35 were found most tolerant to low N conditions and should be used to develop low N tolerant varieties.

Key words: Maize, landrace, heritability, correlation, nitrogen, tolerance, stress

4.1 Introduction

Although maize is the most important and widely grown food crop in Zambia, its grain yield (GY) is low under small-scale farmer conditions. Average GY per district ranges between 0.58t ha^{-1} to 3.1t ha^{-1} among the small-scale farmers who account for over 90% of the farming community in Zambia (CSO, 2006). According to Waddington and Heisey (1997), nitrogen (N) is the most severe and wide spread constraint to maize production as most of the farmers lack cash or credit to access fertilisers. Removal of subsidies on fertilisers by the Zambian government further reduced the use of fertiliser in the country and the fertiliser: maize price ratio (number of kg maize required to purchase one kg fertiliser) increased from 0.9 in 1986 to 2.7 in 1993 (Mungoma and Mwambula, 1997) and to 2.6 in 2007. Nitrogen deficiency in maize production is also reported as a wide spread problem among small-scale farmers in the whole of southern Africa and elsewhere in tropical areas (Waddington and Heisey, 1997; Logrono and Lothrop, 1997; Loomis, 1997). Yield loss due to deficiency in N is reported to be wide spread in the tropics (Mduruma and Ngowi, 1997; Betran et al., 2003).

Nitrogen is an important element to maize production as it promotes vegetative growth, maximizes both kernel initiation and kernel set, and is also key in filling the kernel sink (Below, 1997). Nitrogen deficiency interferes with protein synthesis, induces leaf senescence and therefore reduces the general growth of the maize plant (Bruns and Abel, 2003) thereby limiting yield. In Asia, N deficiency causes yield losses of 10-50% (Logrono and Lothrop, 1997). Santos et al. (1997) observed yield losses of 65.8% when an open pollinated variety that was developed under soils of high fertility was grown under high N conditions (120kg ha^{-1} N added) and low N conditions (no N added).

Increased varietal tolerance to low N stress offers an effective partial solution to enhance maize production and food security among the resource poor and small-scale farmers. Under this strategy plants are able to tolerate deficiency of N by partitioning more N and carbohydrates to the ear. An appropriate breeding strategy can be used to develop genotypes that tolerate the stress and produce high grain yield under both low N and optimal conditions. Few scientists have recently explored this area because it has often been assumed that there is no interaction for GY between N levels and cultivars.

Lafitte et al. (1997) evaluated landraces (LRs) and improved varieties under low N and optimal conditions and found that LRs were superior in grain N concentration but not in GY at both N levels. LRs appeared to have traits with adaptive value for low N conditions since they had been traditionally managed under soils of low fertility over generations. In developing varieties for low N environments, superior genotypes should be selected from germplasm well-adapted to such stress environments. Genetic variance for GY under low N environments is low (Banziger et al., 1997; Betran et al., 2003) and identification of genotypes which tolerate the stress on the basis of GY alone may not be effective. Local unimproved varieties (landraces) should be the preferred germplasm, because they may be able to contribute useful traits with adaptive value for stable production under low N conditions (Lafitte et al., 1997), provided other deleterious traits they carry do not affect their performance in other environments.

Selecting under high inputs increases genetic variance relative to environmental variance and thus increases heritability. This increases the chances of selecting superior genotypes and making breeding progress. It is, however, less effective if the variety is targeted for a low input environment such as that under low N conditions because genetic correlation for GY between the two environments may be low (Banziger et al., 1997). Use of selection environment that differs considerably from the target environment (Indirect selection) is usually not more effective than direct selection in the target environment (Falconer, 1981).

To develop an appropriate breeding strategy in selecting genotypes that tolerate low N conditions, information on gene action is important. Below et al. (1997) reported that additive gene action in Corn Belt germplasm was important; while Betran et al. (2003) reported that non-additive gene action in tropical maize was important. However, these studies have collectively shown that many N use traits were under genetic control and that physiological processes limiting yield differed according to the level of N. Further research in this area is needed to improve strategies in breeding for low N tolerance.

General combining ability (GCA) is the mean performance of a line in all its crosses, expressed as a deviation from the mean of all crosses (Hallauer and Miranda, 1988). Information of GCA effects may be used to estimate gene action of traits. In statistical terms GCA effects are main effects and indicate primarily additive gene action (Falconer, 1981). Effects of GCA can also be used to select superior genotypes under drought conditions. High GCA effects under low N reflect the presence of the desired low N tolerant alleles being sought. Vasal et al. (1992) crossed 88 inbred lines to four testers and used GCA and specific combining ability (SCA) effects to identify and form heterotic groups of maize with subtropical adaptation. In the current study GCA effects could be used to identify populations where gains in tolerance to low N conditions could be effectively made. Betran et al. (2003) reported low GCA effects for GY under low N conditions and that there was crossover type of interaction of GCA effects under low and optimal conditions.

Information on heritability of traits, and their correlation with GY, is important in predicting breeding progress for the low N environment. Banziger et al. (2000) found that information on GY, number of ears per plant (EPP), anthesis-silking interval (ASI) and leaf senescence (Lsene) were important in selecting superior genotypes under low N conditions. Therefore, these traits were measured in the current study. However, in addition to these, tassel size (Tsize) and leaf rolling (Lroll) were also used in selecting genotypes under drought conditions (Edmeades et al. (1999). Lafitte and Banziger (1997) found that selection under drought also improved tolerance to low N conditions by 3.4% per year. Therefore, these two traits and grain texture (Gtext), which farmers used to select their seed (Chapter 2) were also measured in the current study.

This study was carried out to determine: a) tolerance to low N conditions; b) genotype x environment interaction effects; c) heritability of GY and other traits and; d) correlations among traits in landraces of maize grown under low N conditions. The hypothesis tested in the study was that there is adequate genetic variation among maize LRs for low N tolerance that can be improved by selection.

4.2 Materials and methods

4.2.1 Germplasm

4.2.1.1 Landraces, checks and tester

The germplasm for the research study was obtained from CIMMYT (Zimbabwe). These included 96 LRs originally collected from Zambia, four open pollinated varieties (OPVs) released in Zambia as checks (c) and a single cross hybrid (CML312/CML395) as a tester, whose parents are superior for tolerance to drought and low N stress. Check varieties used during 2005/06 and 2006/07 season were obtained from Seed Control and Certification Institute of Zambia (SCCI). The descriptions of the germplasm are presented in Appendices 4.1 and 4.2.

4.2.1.2 Generation of S_1 lines

During the first season (2004/05), all the 96 LRs and check OPVs were planted in a nursery at Chilanga under optimal (112kg N ha^{-1}, 44kg P ha^{-1} and 30kg K ha^{-1}) conditions (see 4.2.2.1). The entries were randomized without replication. The plot size per entry was two rows 5m long, 0.75m between rows, and two plants per hill, spaced 0.5m within the row (22 plants per row; total 44 plants per entry). At least 14 plants were selfed per entry. The nursery was maintained clean of weeds by hand weeding. Planting, self pollination and harvesting were done by hand. Each ear of the harvested S_1 line was stored separately. Fourteen S_1 lines (with at least 200 kernels per ear) for each of the 16 superior landraces (4.2.3.1) were drawn at random.

4.2.1.3 Generation of testcrosses (TCs)

During the 2005/06 season, all the 224 S_1 lines were crossed to a single cross hybrid tester (CML312/CML395) in a nursery which was planted at Nanga under optimal conditions (see 4.2.2.1). The tester has alleles for tolerance to low N (also drought) and has been used in many hybrids in the SADC region. An isolation block was established which was more than 400m from the nearest maize crop. Plot size was 2 rows, 5m long, 0.75m between rows, and two plants per hill spaced 0.5m within the row (22 plants per row; 44 plants per entry). The nursery was maintained clean of weeds by hand weeding. Two rows of a tester were planted after every 6 rows of the entries in one planting as anthesis of the S_1 lines fell within its duration for pollen shed. The S_1 lines were de-tasseled before shedding pollen. Planting, de-tasseling and harvesting were done by hand. Seed harvested for each testcross (TC) was bulked into one family.

4.2.2 Experimental environments

The study was conducted under optimal, low N and drought conditions. The experimental environments are described below:

4.2.2.1 Environment 1: Optimal conditions

A basal dressing fertiliser of 20kg N ha^{-1}, 44kg P ha^{-1} and 30kg K ha^{-1} was applied at planting, and a top dressing fertiliser of 92kg N ha^{-1} was applied 30d later. Trials and nurseries depended on summer rainfall for water (Table 4.1). The trials were conducted at Chilanga during 2004/05 to 2006/07 seasons, and at Golden Valley during 2006/07 season. The nurseries were conducted at Chilanga during 2004/05 and Nanga during 2005/06 seasons.

Table 4.1: Features of the experimental sites and the amount of rainfall received (mm) at the trial sites during the study period

	Location of trial site			Amount of water during seasons (mm)		
Trial site	Latitude (South)	Longitude (East)	Altitude (m)	2004/05	2005/06	2006/07
Rain fed						
Chilanga	15.55°	26.26°	1227	640.8	910.5	568.0
Golden Valley	14.97°	28.10°	1148	825.5	905.1	1167.1
Kabwe	14.44°	28.45°	1172	730.1	871.3	1067.0
Nanga	15.86°	27.76°	1044	583.7	790.8	663.9
Irrigated				Amount of irrigation water (mm)		
Nanga	15.86°	27.76°	1044	640.0	640.0	-
Lusitu	16.13°	28.83°	480	-	-	640.0
Luangwa	15.10°	30.18°	373	-	-	640.0

Long term annual rainfall at Chilanga, Golden Valley, Nanga and Kabwe is estimated as 800-1000mm (Bunyolo et al., 1997); while at Lusitu and Luangwa the estimate is 600-800mm. Initial soil fertility at each trial (Table 4.2), during the evaluation of testcrosses (2006/07 season), was determined by Zambia Agriculture Research Institute (ZARI) based on Woode (1988).

4.2.2.2 Environment 2: Low N conditions

The trial was located at Golden Valley during 2004/05, 2005/06 and 2006/07 seasons and at Kabwe during 2006/07. The respective blocks had been depleted of N by continuously growing maize at high density (extract crop) for several previous seasons and removing the biomass after each crop. Nitrogen was not applied to the trials. However, the recommended 44kg P ha^{-1} and 30kg K ha^{-1} were applied at planting. The trial depended on summer rainfall for water (Table 4.1). Initial soil fertility at each trial was determined prior to planting (Table 4.2).

Table 4.2: Results of soil analysis at trial sites

Trial site	Soil depth (mm)	Trial	Hand Text	pH ($CaCl_2$)	Org (C%)	N (%)	P (ppm)	K (me%)
G.Valley	200	Optimal	SCL	5.7	2.13	0.15	8	0.97
	400	Optimal	SCL	5.1	1.94	0.14	5	0.94
Chilanga	200	Optimal	SCL	6.9	2.13	0.15	18	0.77
	400	Optimal	SCL	6.4	0.33	0.02	3	0.61
G.Valley	200	Low N	SCL	5.7	1.20	0.09	36	3.40
	400	Low N	SCL	5.6	0.42	0.03	6	3.38
Kabwe	200	Low N	SL	5.3	1.19	0.09	38	0.33
	400	Low N	SL	5.1	1.17	0.08	28	0.31
Lusitu	200	Drought	SL	7.6	0.64	0.04	86	1.00
	400	Drought	SL	7.5	0.11	0.01	69	0.51
Luangwa	200	Drought	SCL	7.6	0.44	0.03	96	0.97
	400	Drought	SCL	7.7	0.37	0.02	84	0.77

Key for soil texture: S = Sand, LS=Loamy Sand, SL= Sandy Loam, SC= Sandy Clay, SCL= Sandy Clay Loam

Key for soil pH$_2$: < 4.0 = Extremely acid, 5.0-4.0 = Strongly acid, 5.0-7.0 Medium acid, 7.0=Neutral, >7.0 Alkaline.

4.2.2.3: Drought conditions

The trial was located at Nanga during 2004/05 and 2005/06 seasons, and was conducted at Lusitu and Luangwa during 2006/07. Full fertilisation was applied as basal dressing at the rate 20kg N ha^{-1}, 44kg P ha^{-1}, 30kg K ha^{-1} at planting. Top dressing fertiliser of 92kg N ha^{-1} was applied 30d after planting. The experiment was conducted during the dry season (May-October) to control water supply. It depended on irrigation water and an estimated 640mm of water was applied per season. Irrigation was withdrawn for 35d about 60d after planting (about a week before anthesis of the earliest entry) and when soil moisture content was below 50% of the field capacity. Time to withdraw irrigation depended on the amount of heat units the genotypes required to flower during the earlier optimal trial in summer. Soil moisture level (volume of water per volume of soil) at the trial sites was monitored by measurements every 10d (at 300mm, 600mm and 900mm depth) by the Soil Physics Laboratory at ZARI. Two irrigations were applied after the moisture withdrawal period.

4.2.3 Experimental design and management

4.2.3.1 Performance trials of 96 landraces plus four check varieties

The performance trials were conducted as a 10 x 10 simple lattice design with two replications under optimal, low N and drought conditions at Chilanga, Golden Valley and Nanga, respectively during the 2004/05 season. The plot size was one row, 5m long, 0.75m between rows, and two plants per hill spaced 0.5m within the row (22 plants per row; total 22 plants per entry). The established plant density was 53,000 plant per ha. The trials were maintained clean of weeds by hand weeding. Planting and harvesting were done by hand. Two border rows and plants at two hills at either end of the plot were excluded from the harvest (whole plot).

Anthesis day (AD) and silking day (SD) were obtained as number of days after planting until 50% of plants were shedding pollen and silking, respectively. The ASI was calculated as SD-AD. Leaf rolling (Lroll) was measured by scoring on a scale from zero (unrolled, turgid leaves, desirable) to one (severely rolled leaves, undesirable) while Lsene was measured during grain filling by estimating the fraction of area which had turned brown (dead leaf). Tassel size (Tsize) was determined as the number of primary branches of the tassel per plant. At harvest, the number of ears with at least one fully developed grain expressed as a fraction of number plants at harvest was used to determine EPP. Grain yield was measured as weight of shelled grains (t ha^{-1}) adjusted to 12.5% grain moisture. Grain texture was measured on a scale 0 to 1 where; kernel of deep depression (fully dent) = 0, medium depression = 0.25, mild depression = 0.5, roughly smooth = 0.75, smooth (fully flint) = 1.0.

Data were analyzed within each environment using GenStat (Payne et al., 2007) and genotypic means were computed. Under each trial a selection index (SI) was calculated for respective traits in order to combine information on secondary traits with that of GY. Calculation of the selection index was as described by Banziger et al. (2000). Information on GY, EPP, ASI and Lsene was used in calculating selection indices as in Table 4.3.

Table 4.3: Weights of secondary traits

Trait	Weight	Preference
Grain yield	5	Increasing
Number of ears per plant	2	Increasing
Leaf senescence	-2	Reducing
Anthesis-silking interval	-1	Reducing

The best four LRs (4% selection intensity) under optimal, low N, drought and across the three environments were identified using the index. Fourteen S_1 lines from each of the 16 identified LR were randomly selected (a total of 224 S_1 lines). The performance of the S_1 lines per se was evaluated and at the same time, these were crossed to the tester and testcrosses evaluated for performance in the 2005/06 season.

4.2.3.2 Evaluation of S_1 lines for performance per se

All the 224 S_1 lines and one check (ZM521) were planted in performance trials under optimal, low N and drought conditions at Chilanga, Golden Valley and Nanga, respectively, during the 2005/06 season. Each trial was laid out as a 15 x 15 lattice design with two replications under each environment. The plot size was one row, 5m long, 0.75m between rows, and two plants per hill spaced 0.5m within the row (22 plants per row; 22 plants per entry). The established plant density was 53,000 plant per ha. The trials were maintained clean of weeds by hand weeding.

Recording of main characteristics and analysis of S_1 lines per se data were as in performance trial described earlier (see section 4.2.3.2). Planting and harvesting were done by hand. Two border rows and plants at two hills at either end of the plot were excluded from the harvest (whole plot).

4.2.3.3 Evaluation of testcrosses

The best 22 S_1 lines under optimal, low N, drought and across the environments (88 in total, 10% selection intensity) were identified and their respective TCs selected for evaluation during the 2006/07 season. The 88 TCs and 12 checks (Appendix 4.2) were evaluated in performance trials under low N and optimal conditions at Golden Valley (GV) and Kabwe. Above normal rainfall was received at GV and plants were sometimes under waterlogged conditions (Table 4.1). In order to obtain adequate seed for evaluation, all the bulked seeds of each of the selected TC were mixed and a sample drawn at random. The trials were laid out as a 10 x 10 lattice design with two replications. The checks included seven popular OPVs, four popular hybrids and a LR. The plot size was one row, 5m long, 0.75m between rows, and two plants per hill spaced 0.5m within the row (22 plants per row; 22 plants per entry). The established plant density was 53,000 plant per ha. The trials were maintained clean of weeds by hand weeding. Recording of main characteristics was as in the performance trial described earlier (section 4.2.3.1). Planting and harvesting were done by hand.

4.2.3.4 Analysis of testcross data

Data was analyzed using GenStat (Payne et al., 2007) using the following model: y= μ + r.g. + g + Є where μ = grand mean, r = replicate effects, g = genotype effects, and Є = experimental error associated with the trial. A selection index (SI) for each entry per trial was determined as in section 4.2.3.1. Phenotypic correlations among various traits were also calculated. Relative grain yield of a genotype was calculated by expressing its GY as percentage of the mean grain yield of the trial. Grain yield greater than GY of the tester expressed heterosis of a genotype. Low N tolerance index (LNTI) was defined as GY reduction due to low N stress in comparison to that under optimal conditions at the same site, and was calculated as: (1 – (GY_{LN}/GY_{OP}) x 100% where: GY_{LN} = grain yield under low N environment (low N stress) and GY_{OP} = grain yield under optimal environment (non stress).

Analysis of variance for GY was performed for each trial and main effects of the factors and their interaction effects were analyzed in terms of their importance in influencing GY. Varieties with significant GE interaction effects were assessed for crossover type of interaction effects using ranks of genotypes at Golden Valley (GV) and Kabwe. A genotype that changed its ranking reflected a crossover type of GE interaction effect. Estimates of genotypic variance (V_G) and error variances (V_E) were calculated from the expected mean squares of the analysis of variance (Falconer and Mackay, 1996). Broad sense heritabilities (H^2) for traits were calculated as: $H^2 = V_G / (V_G + V_E/r)$ where r = number of replicates. Genetic correlations (r_G) were calculated as follows: $r_G = Cov_G /$ sqrt $[V_G(\text{High N})*V_G(\text{Low N})]$, where Cov_G = genetic covariance, sqrt = square root of, as in Bolanos and Edmeades (1996). General combining ability (GCA) effects for each trait and genotype were calculated as a deviation from the grand mean (Hallauer and Miranda, 1989).

4.3 Results

4.3.1 Performance of landraces under low N and optimal conditions

Analysis of variance showed that differences in the performance of LRs were significant ($p \leq 0.05$) for GY under low N. Grain yield ranged from 1.36t ha^{-1} (LR67) to 6.57t ha^{-1} (LR35) under optimal conditions and ranged from 0t ha^{-1} (LR34) to 2.67t ha^{-1} (LR79) under low N conditions. The best check under both conditions was ZM421 which ranked 2nd under optimal (6.48t ha^{-1}) and 8th under low N conditions (1.56t ha^{-1}). Under low N, GY by the best check was significantly different ($p \leq 0.05$) from that of the best genotype (LR79). The four highest yielding LRs under low N conditions were LR49, LR4, LR79 and LR93 in that order (Table 4.4). The 10 lowest yielding genotypes were all LRs with LR34 collected from Masaiti failing to achieve any GY. Each genotype under optimal conditions at GV achieved GY above the trial mean of the low N trial also at GV.

Of the top 10 genotypes, based on selection index, only one was a check (ZM421) and it ranked 8th. Landraces LR49, LR4, LR79 and LR93 were ranked 1st, 2nd, 3rd and 4th respectively, in tolerance to low N, maintaining their ranking in GY. Among the top 10 most tolerant genotypes, LR49, LR79, LR93 and LR11 were selected as they had many S_1 lines and adequate amount of seed per S_1. All the 10 least yielding genotypes were LRs with the lowest being LR11 (Sesheke) that failed to achieve any yield.

Table 4.4: Top and bottom landraces under low N (based on selection index) and optimal conditions (based on GY alone)

Performance under Low N				Performance under optimal	
Entry	GY (t ha^{-1})	Rank GY	Rank SI	LR based on GY	GY (t ha^{-1})
Top 10					
LR49	2.67	1	1	LR35	6.57
LR4	2.04	2	2	ZM421 (c)	6.48
LR79	1.66	3	3	LR5	5.82
LR93	1.64	4	4	LR26	5.81
LR69	1.34	11	5	LR49	5.66
LR19	1.26	15	6	LR86	5.60
LR1	1.44	7	7	LR53	5.59
ZM421-c	1.56	6	8	LR16	5.57
LR28	1.57	5	9	LR33	5.55
LR11	1.27	13	10	LR76	5.48
Mean	1.64				5.81
Bottom 10					
LR45	0.44	87	91	LR29	2.55
LR35	0.42	90	92	LR31	2.43
LR59	0.34	93	93	LR17	2.42
LR40	0.26	94	94	LR68	2.40
LR82	0.17	98	95	LR69	2.39
LR14	0.44	88	96	LR58	2.34
LR87	0.21	97	97	LR64	2.28
LR33	0.24	95	98	LR62	2.22
LR88	0.17	99	99	LR88	2.15
LR34	0.00	100	100	LR67	1.36
Mean	0.27				2.25
Trial Statistics					
Max	2.67				6.57
Min	0.00				1.36
Mean	0.84				3.85
SE	± 0.48				± 1.30
LSD	0.95				2.57
Pvalue	0.012				0.103

4.3.2 Performance Per Se Of S_1 Lines under low N and optimal conditions

It was found that S_1 lines were significantly different ($p \leq 0.05$) for GY under low N. Grain yield ranged from 0.16t ha^{-1} (S_1 line 59, progeny of LR21) to 11.14t ha^{-1} (S_1 line 14, progeny of LR38) under optimal conditions, while it ranged from 0t ha^{-1} (S_1 line 167, progeny of LR5) to 2.46t ha^{-1} (check, ZM521) under low N conditions (Table 4.5). The 10 highest yielding S_1 lines were progenies of LR40 (S_1 line 193), LR38 (S_1 line 11), LR26 (S_1 line 28), LR21 (S_1 line 68), LR38 (S_1 line 13), LR93 (S_1 line 109), LR84 (S_1 line 127), LR26 (S_1 line 25), LR84 (S_1 line 135), and LR86 (S_1 line 35) in that order.

Based on the selection index, S_1 line 80 (progeny of LR11) was the most tolerant to low N while S_1 line 11 (progeny of LR38) was next (Table 4.5). ZM521 was ranked third while S_1 line 13 (progeny of LR38) was ranked fourth in tolerance to low N stress.

Despite LR49 being found the most tolerant genotype to low N in the first season (2004/05), none of its S_1 lines were among the top 25 (11%) under low N conditions. In fact, the highest yielding S_1 line of the LR ranked 51st out of the 225 genotypes evaluated. However, LR11 (ranked 10th in tolerance to low N) had its S_1 lines ranked first and 11th in tolerance to low N. The other two selected LRs in season 1 only contributed one S_1 line each ranked 12th and 16th for LR93 and LR79, respectively. Other LRs which were not found superior under low N conditions (but found best under drought, optimal or across the three environments) contributed S_1 lines among the top 25 genotypes tolerant to low N. Therefore of the 56 S_1 lines (4 landraces x 14 S_1 lines) whose parents were superior under low N conditions only about 7% were tolerant to low N.

Table 4.5: Top and bottom S_1 lines under low N (based on SI) and optimal conditions (based on GY alone)

Performance under low N					Performance under optimal		
S_1 line	LR	GY (t ha^{-1})	Rank GY	Rank SI	S_1 line	LR	GY (t ha^{-1})
Top 10							
80	LR11	1.95	12	1	14	LR38	11.14
11	LR38	2.29	3	2	32	LR86	8.13
ZM521-c	ZM521	2.46	1	3	183	LR40	8.12
13	LR38	2.24	6	4	53	LR76	8.08
68	LR21	2.26	5	5	29	LR86	7.87
38	LR86	1.87	14	6	193	LR40	7.86
193	LR40	2.39	2	7	136	LR84	7.80
25	LR26	2.09	9	8	5	LR38	7.36
28	LR26	2.28	4	9	174	LR35	7.24
165	LR5	1.62	27	10	45	LR76	6.82
Mean		2.14					8.04
Bottom 10							
196	LR40	0.14	208	216	117	LR74	1.08
214	LR49	0.51	167	217	84	LR11	1.03
223	LR49	0.24	201	218	203	LR79	1.01
116	LR74	0.23	204	219	213	LR49	0.91
224	LR49	0.02	219	220	97	LR12	0.79
97	LR12	0.10	212	221	138	LR84	0.68
91	LR12	0.07	217	222	214	LR49	0.68
180	LR35	0.10	211	223	25	LR26	0.52
222	LR49	0.00	221	224	43	LR76	0.19
87	LR12	0.11	210	225	59	LR21	0.16
Mean		0.15					0.70
Trial Statistics							
Max		2.46					11.14
Min		0.00					0.16
Mean		0.90					3.69
SE		± 0.47					± 1.86
LSD		0.93					3.67
P value		0.00					0.001

4.3.3 Performance of testcrosses under low N and optimal environments

4.3.3.1 Grain yield of testcrosses

The best 22 S_1 lines (10%) were selected and their respective TCs evaluated for tolerance to low N stress. In order to determine homogeneity of variances between the trial at Golden Valley and that at Kabwe, respective mean square error (MSE) at the sites was used. The ratio of MSE_{large} to MSE_{small} between the two sites was 13 hence the results for each trial site are reported separately (Table 4.6). According to Mead et al. (2003) when the ratio of MSE_{large} to MSE_{small} was above 4 (or 6 if number of sites is large), combined analysis was not effective because of non-homogeneity of variances. Genotypes were found significantly different under low N (GV and Kabwe) and optimal (GV) conditions.

These results show that genotypes achieved higher GY under low N at Golden Valley than at Kabwe. Grain yields at Golden Valley ranged from 0.22 to 2.24t ha^{-1}, while at Kabwe GY ranged from 0.09 to 0.98t ha^{-1}. However, the best yielder at Golden Valley (TC56 progeny of LR84 with 2.24t ha^{-1}) only produced 0.48t ha^{-1} at Kabwe. The highest yielding line at Kabwe didn't make it into the top 10 either.

Across sites performance of the genotypes was based on the average rank of GY between the sites (calculated as arithmetic mean of ranks of a genotype in GY under low N at GV and Kabwe). Testcross TC77 (progeny of LR40) with 2.01t ha^{-1} at GV and 0.73t ha^{-1} at Kabwe was the highest yielding genotype over locations (Table 4.6). The lowest yielding genotype was a check MMV400 that achieved 0.57 and 0.26t ha^{-1} at GV and Kabwe, respectively. All the top 10 genotypes for GY were TCs and the best check was a LR and ranked 20th. The 10 highest yielding genotypes were also superior to both the best check, and the tester which ranked 82nd.

Table 4.6: Top and bottom testcrosses (TCs) and checks under low N based on average rank of grain yield when grown at Golden Valley and Kabwe, Zambia under optimal and low N conditions.

TC	LR	GY – Low N			GY – optimal (GV)	Rel. GY reduction (%)	% grain yield above	
		GV	Kabwe	Average Rank			Best check	Tester
Top 10								
TC77	LR40	2.01	0.73	6.00	1.85	-9.00	16.00	112.00
TC72	LR35	2.22	0.61	10.00	1.89	-18.00	19.00	119.00
TC28	LR76	1.75	0.84	11.50	2.20	21.00	9.00	100.00
TC53	LR84	1.78	0.65	14.50	1.88	5.00	18.00	116.00
TC49	LR84	1.58	0.92	15.50	2.22	29.00	11.00	103.00
TC35	LR12	1.56	0.73	18.00	2.13	27.00	2.00	87.00
TC32	LR11	1.97	0.55	19.50	1.96	-1.00	12.00	105.00
TC54	LR84	1.88	0.58	20.00	1.28	-48.00	6.00	95.00
TC70	LR35	1.68	0.61	20.00	1.69	1.00	1.00	85.00
TC27	LR76	1.42	0.81	22.50	1.67	15.00	1.00	85.00
Mean		1.78	0.70		1.88			
Bottom 10								
82 (c)	MMV600	1.09	0.27	80.50	1.60	32.00	-30.00	28.00
TC2	LR38	0.52	0.45	81.00	2.12	76.00	-50.00	-20.00
TC65	LR85	0.96	0.35	82.50	1.84	48.00	-30.00	26.00
TC51	LR84	1.14	0.09	83.50	2.09	45.00	-50.00	-1.00
TC21	LR86	0.54	0.41	83.50	1.67	68.00	-50.00	-10.00
TC12	LR86	1.13	0.11	84.00	2.10	46.00	-30.00	35.00
TC86	LR79	0.88	0.34	86.00	2.39	63.00	-40.00	15.00
TC64	LR85	0.61	0.37	86.50	1.74	65.00	-50.00	-10.00
TC26	LR76	0.73	0.32	88.50	1.26	43.00	-50.00	-10.00
100(c)	MMV400	0.57	0.26	93.50	1.40	59.00	-60.00	-20.00
Mean		0.82	0.30		1.82			
Statistics								
Max		2.24	0.98	93.50	2.69	88.00	20.00	120.00
Min		0.22	0.09	6.00	0.53	-254.00	-60.00	-25.00
Mean		1.34	0.48	50.50	1.91	26.00	-20.00	51.00
SE		±0.55	±0.14		±0.39			
LSD		1.10	0.28		0.78			
P value		0.00	0.00		0.03			

In comparing GY of genotypes under the low N and optimal trials both at Golden Valley, it was found that the mean trial yield (environmental index) was higher under optimal conditions (1.91t ha^{-1}) than under low N conditions (1.34t ha^{-1}). However, some genotypes yielded more under low N than under the optimal environment. Testcrosses

TC56 and TC72 yielded more under low N than optimal environment, by 18.3% and 17.7%, respectively. The Low N tolerant index (LNTI), also called relative yield reduction, ranged from -254% to 88% with an average of 26% (Table 4.6). Testcross TC56 and TC72 were ranked 5th and 6th respectively, in LNTI (4.7). The best genotype in LNTI was TC16 (progeny of LR86) which yielded 254% more under low N (1.87t ha^{-1}) than under optimal conditions (0.53t ha^{-1}). Among the top 10 genotypes in GY (based on average ranks), four had negative LNTI while the bottom 10 had yield reductions of between 32 and 76% (Table 4.6).

Table 4.7: Ranking of testcrosses under low N based on average rank

		Grain yield – low N		Selection index			
TC	Landrace	GV	Kabwe	LNTI	GV	Kabwe	Rank of Average GY Rank
Top 10							
TC77	LR40	6	6	8	28	5	1
TC72	LR35	2	18	6	4	21	2
TC28	LR76	20	3	41	9	3	3
TC53	LR84	17	12	20	10	25	4
TC49	LR84	29	2	50	14	2	5
TC35	LR12	31	5	49	42	12	6
TC32	LR11	8	31	14	2	33	7
TC54	LR84	14	26	2	15	46	8
TC70	LR35	23	17	17	40	26	9
TC27	LR76	41	4	31	27	4	10
Bottom 10							
82 (c)	MMV600	72	89	54	72	99	91
TC2	LR38	98	64	98	96	65	92
TC65	LR85	83	82	76	82	74	93
TC21	LR86	97	70	95	88	71	94
TC51	LR84	67	100	69	48	97	95
TC12	LR86	69	99	70	66	98	96
TC86	LR79	89	83	93	91	83	97
TC64	LR85	94	79	94	94	75	98
TC26	LR76	92	85	65	93	77	99
100 (c)	MMV400	96	91	91	98	94	100

Genotypes were ranked in decreasing order in GY under low N (at GV and Kabwe) and under optimal conditions (GV). The best genotype ranked 1 while the worst was ranked 100. Similarly, the genotypes were ranked in decreasing order in LNTI between the low

N trial at GV and the optimal trial at the same site. The rank were then correlated (r). Rank of GY under low N conditions was significantly correlated (r = 0.904*) with LNTI rank but was negatively correlated (r = -0.441*) with rank under optimal conditions (Table 4.8). Similarly, significant rank correlation was also found between average rank and rank in GY at Golden Valley (r = 0.732*) and Kabwe (r = 0.735*).

Table 4.8: Correlation of ranks in GY and LNTI under low N and optimal conditions

Average rank	1				
LNTI		1			
GY – Optimal (GV)		-0.441*	1		
GY - Low N (GV)	0.732*	0.904*	-0.065	1	
GY - Low N (Kabwe)	0.735*		0.125	0.085	1
	Average rank	LNTI	GY - optimal (GV)	GY - low N (GV)	GY - Low N (Kabwe)

* Significant at p ≤ 0.05

4.3.3.2 Tolerance of testcrosses to low N

Based on selection indices TC56 (progeny of LR84) was the most tolerant to low N stress at GV and TC19 (progeny of LR86) at Kabwe (Table 4.9). The five most tolerant genotypes under low N conditions at GV were progenies of LR84, LR11, LR93, LR35 and LR38 while at Kabwe they were LR86, LR84, LR76 (contributed two TCs) and LR40. Among the top 10 genotypes at GV was one check MM603 (ranked 7th) while at Kabwe none of the checks was among the top 10 in tolerating low N stress. Among the 10 least tolerant genotypes for Low N stress based on the SI were two checks (Pop25 and MMV400) at GV and three checks (MMV400, MMV400 and Pool16) at Kabwe.

Genotypes were ranked based on average GY under low N between GV and Kabwe. It was found that the best five testcrosses were progenies of LR40, LR35, LR76 and LR84 (contributed two TCs). These LRs were among the 10 LRs that contributed TCs which were most tolerant to low N stress based on selection indices at both GV and Kabwe (Table 4.9). None of the checks was among the top 10 genotypes based on average GY but two of them (MMV600 and MMV400) were among the 10 least tolerant genotypes based on the average rank of GY.

The most tolerant genotypes to low N stress based on LNTI were progenies of LR86 (two TCs) and LR84 (two Tcs). The best check (Pool16) ranked 4th and was the only check among the top 10 in LNTI. However MMV400 and Pop25 were among the poorest for LNTI.

Table 4.9: Top and bottom 10 genotypes in selection index, average GY and LNTI under low N conditions

Based on selection index				Based on grain yield			
Golden Valley		Kabwe		Average GY rank		LNTI	
TC	LR	TC	LR	TC	LR	TC	LR
Top 10							
TC56	LR84	TC19	LR 86	TC77	LR40	TC16	LR86
TC32	LR11	TC49	LR 84	TC72	LR35	TC54	LR84
TC39	LR93	TC28	LR 76	TC28	LR76	TC10	LR86
TC72	LR35	TC27	LR 76	TC53	LR84	Pool16	Pool16
TC7	LR38	TC77	LR 40	TC49	LR84	TC56	LR84
TC85	LR79	TC17	LR 86	TC35	LR12	TC72	LR35
MM603	MM603	TC80	LR 40	TC32	LR11	TC25	LR76
TC37	LR12	TC31	LR 21	TC54	LR84	TC77	LR40
TC28	LR76	TC55	LR 84	TC70	LR35	TC83	LR40
TC53	LR84	TC52	LR 84	TC27	LR76	TC85	LR79
Bottom 10							
TC86	LR79	TC23	LR 76	MMV600	MMV600	MMV400	MMV400
Pop25	Pop25	TC62	LR 85	TC2	LR38	TC22	LR76
TC26	LR76	TC16	LR 86	TC65	LR85	TC86	LR79
TC64	LR85	MMV400	MMV400	TC21	LR86	TC64	LR85
TC15	LR21	TC57	LR 84	TC51	LR84	TC21	LR86
TC2	LR38	TC29	LR 21	TC12	LR86	TC15	LR21
TC40	LR93	TC51	LR 84	TC86	LR79	Pop25	Pop25
MMV400	MMV400	TC12	LR 86	TC64	LR85	TC2	LR38
TC92	LR49	MMV600	MMV600	TC26	LR76	TC24	LR76
TC24	LR76	Pool16	Pool16	MMV400	MMV400	TC92	LR49

The highest yielding genotype under low N conditions based on average rank was TC77 (progeny of LR40), which ranked 5th at Kabwe and 28th at GV in tolerance to low N stress based on SI and 8th in LNTI (Table 4.10). The most low N tolerant genotype at GV based on SI was TC 56 (progeny of LR84) which ranked 15th in average rank of GY and

5th in LNTI. The most low N tolerant genotype at Kabwe based on SI was TC19 (progeny of LR86) which ranked 25th in average rank of GY and 74th in LNTI. TC16 (progeny of 86) which was the best genotype in LNTI was 56th in average GY and 20th in SI at GV but 93rd in SI at Kabwe.

The results also show that only LR11 and LR79 which were among the top 10 genotypes in tolerance to low N during 2004/05 season contributed testcrosses (TC32 and TC85, respectively) which were among the top 10 genotypes under low N conditions based on SI. Other TCs among the top 10 were derived from S_1 lines of the best LRs under drought, optimal and across the three environments. However, all the top 10 TCs under low N conditions at Kabwe were progenies of LRs which were among the top 10 genotypes (based on SI) under drought conditions during 2004/05 season. Five of the top 10 genotypes under low N at GV were progenies of LRs which were among the top 10 genotypes under drought conditions during the 2004/05 season. LR35, LR76 and LR86 which were among the top 10 genotypes based on GY under optimal conditions (2004/05 seson) contributed TCs which were among the top 10 genotypes under low N based on SI. They included TC72 (progeny of LR35) and TC28 (progeny of LR76) at Golden Valley. Others were TC27 and TC28 (both progenies of LR76), and TC17 and TC19 (both progenies of LR86). The best check in tolerance to low N stress was MM603 which ranked 7th while ZM421 (21st) was the second best check at GV. ZM421 was best check under low N at Kabwe but ranked 29th based on SI

Table 4.10: Ranking of testcrosses in low N tolerance based on average grain yield at Golden Valley (GV) and Kabwe, Zambia.

			Selection index		
TC	LR	Average rank of GY	GV	Kabwe	LNTI
TC77	LR40	6.0	28	5	8
TC72	LR35	10.0	4	21	6
TC28	LR76	11.5	9	3	41
TC53	LR84	14.5	10	25	20
TC49	LR84	15.5	14	2	50
TC35	LR12	18.0	42	12	49
TC32	LR11	19.5	2	33	14
TC54	LR84	20.0	15	46	2
TC70	LR35	20.0	40	26	17
TC27	LR76	22.5	27	4	31
MMV600	MMV600	80.5	72	99	54
TC2	LR38	81.0	96	65	98
TC65	LR85	82.5	82	74	76
TC21	LR86	83.5	88	71	95
TC51	LR84	83.5	48	97	69
TC12	LR86	84.0	66	98	70
TC86	LR79	86.0	91	83	93
TC64	LR85	86.5	94	75	94
TC26	LR76	88.5	93	77	65
MMV400	MMV400	93.5	98	94	91

LNTI denotes Low N tolerant index and is also called relative yield reduction

Based on rank of selection indices, the top 10 genotypes in tolerance to low N stress were selected equally from Golden valley and Kabwe (Table 4.9). The best genotype under optimal conditions across sites was the tester which achieved 2.46t ha^{-1} at GV and 5.44t ha^{-1} at Chilanga (Table 4.11). None of the top 10 TCs were derived from LRs that were among the top 10 under low N conditions in the first season (2004/05). However, they included three TCs of LR86 that was among the best 10 in GY under optimal conditions during the 2004/05 season.The best 10 genotypes under optimal conditions were selected based on average rank of GY at Chilanga and at Golden Valley.

Table 4.11: Grain yield of testcrosses under optimal conditions in order of average rank

		GY (t ha^{-1})		Rank of genotype		
TC/Check (c)	Landrace	GV	Chilanga	GV	Chilanga	Average Rank
Top 10						
96 (c)	Tester	2.46	5.44	4	6	1
TC7	LR38	2.32	5.52	10	4	2
TC17	LR86	2.68	4.78	1	13	3
TC52	LR84	2.28	5.23	13	9	4
TC13	LR86	2.54	4.44	3	24	5
TC51	LR84	2.09	7.01	31	2	6
TC66	LR85	2.14	5.22	23	10	7
TC19	LR86	2.25	4.52	16	22	8
TC48	LR74	2.28	4.41	12	26	9
TC37	LR12	2.11	4.61	24	20	10
Mean		2.32	5.12			
Bottom 10						
TC20	LR86	1.75	2.37	68	91	91
TC59	LR84	1.72	2.48	77	89	92
TC83	LR40	1.62	2.70	87	84	93
TC45	LR74	1.72	1.65	75	97	94
82 (c)	MMV600	1.60	2.65	88	85	95
98 (c)	ZM521	1.72	1.26	76	98	96
TC42	LR93	1.60	1.90	89	96	97
87 (c)	Pool16	1.17	2.41	99	90	98
100 (c)	MMV400	1.40	2.20	95	94	99
TC16	LR86	0.53	2.29	100	93	100
Mean		1.48	2.19			
Trial Statistics						
Max		2.68	7.30			
Min		0.53	0.13			
Mean		1.91	3.64			
SE		±0.39	±1.43			
LSD		0.78	3.06			
P value		0.03	0.07			

4.3.4 General Combining Ability (GCA) estimates of S_1 lines

In estimating the GCA effects deviations from the grand mean were divided by the standard deviation among the means, so that everything is expressed in terms of number of standard deviations centred around a mean of zero. The checks were left out of the calculations of the mean, since they were not crossed to the common tester. Values greater than two (t-test) were significant ($p \leq 0.05$).

The results showed that all the 10 highest yielding genotypes under low N and optimal conditions at GV had significant ($p \leq 0.05$) positive GCA effects for GY. The majority of these genotypes had significant GCA effects for Lsene, EPP and Gtext under low N than optimal conditions (Table 4.12). Half of the genotypes had significant ($p \leq 0.05$) GCA effects for Lroll under low N conditions. However, the GCA effects for ASI and Tsize were not significant ($p \leq 0.05$) under both low N and optimal conditions.

Table 4.12: GCA effects for GY and secondary traits under low N and optimal conditions at GV

			GCA Values (number of standard deviations)						
TC	Landrace	GY (t ha^{-1})	GY	ASI	Tsize	Lsene	EPP	Lroll	Gtext
Top 10 under low N									
TC56	LR84	2.24	2.04*	0.53	0.28	-0.20	2.39*	0.95*	0.84*
TC72	LR35	2.22	1.98*	-0.92	0.22	2.21*	0.96*	-0.44	-0.62
TC7	LR38	2.18	1.90*	-0.33	1.24	0.98*	0.29*	1.96*	0.81*
TC37	LR12	2.11	1.73*	0.09	0.19	0.62*	0.41*	0.54*	0.40*
TC1	LR38	2.03	1.54*	0.15	-0.02	1.20*	0.49*	-0.50	-0.38
TC77	LR40	2.01	1.50*	1.22	-1.02	2.16*	0.83*	0.21	0.41*
TC46	LR74	2.01	1.50*	-0.48	0.87	0.72*	0.24	0.63*	1.32*
TC32	LR11	1.97	1.41*	-1.16	-0.07	-0.80	1.25*	-0.46	-0.70
TC85	LR79	1.95	1.36*	0.03	0.61	0.84*	1.65*	-0.26	-0.39
TC78	LR40	1.94	1.33*	-0.79	1.42	0.83*	-0.50	1.78*	-0.60
Top 10 under Optimal									
TC17	LR86	2.68	2.34*	-0.08	0.03	-0.04	0.46*	0.00	-2.52
TC22	LR76	2.62	2.13*	-0.27	0.00	-0.67	0.08	0.00	1.30*
TC13	LR86	2.54	1.89*	-0.02	-1.18	-0.53	-1.88	0.00	-1.28
TC15	LR21	2.39	1.44*	0.32	-0.18	0.63*	-0.70	0.00	-0.23
TC86	LR79	2.39	1.44*	0.27	0.67	-0.16	0.36*	0.00	-1.81
TC50	LR84	2.35	1.31*	1.10	1.89	0.59*	-0.71	0.00	-1.55
TC78	LR40	2.35	1.31*	1.11	-0.99	-0.46	-3.79	0.00	0.46*
TC89	LR35	2.34	1.28*	0.16	-0.66	0.07	2.21*	0.00	-0.94
TC7	LR38	2.32	1.23*	-0.12	0.61	0.20*	-0.03	0.00	0.45*
TC81	LR40	2.30	1.17*	-0.62	-3.06	0.22*	0.17	0.00	-1.63

*GCA effects significantly different to zero

4.3.5 Phenotypic correlation of GY with secondary traits under low N and optimal conditions

Phenotypic correlations (r) of GY with secondary traits under low N and optimal environments from GV were compared. The results showed that GY correlated significantly ($p \leq 0.05$) with EPP (r= 0.551*), Gtext (r= -0.233*), Lsene (r= 0.199*) and Tsize (r= 0.210*) under low N conditions (Table 4.13). Grain yield was non-significantly correlated with ASI (r= -0.092) and Lroll (r= 0.083). GY correlated significantly ($p \leq 0.05$) with only Lsene (r= -0.223*) and Gtext (r= -0.221*) under optimal conditions.

Table 4.13: Correlations of GY with some secondary traits under low N and optimal conditions

Trait	Correlation (r) with GY under low N conditions	Correlation (r) with GY under optimal conditions
ASI	-0.092	0.046
EPP	0.551*	-0.037
Gtext	-0.233*	-0.221*
Lroll	0.083	
Lsene	0.199*	-0.223*
Tsize	0.210*	0.035

* Significant at $p \leq 0.05$

4.3.6 Heritability estimates of secondary traits and grain yield

Broad sense heritability (H^2) for GY was 0.38 under low N conditions at GV and was lower than that of ASI and Tsize (Table 4.14). Under optimal conditions also at GV, H^2 was 0.32 and was lower than that for Tsize, and Gtext. Golden Valley received above normal rainfall during the 2006/07 season and the optimal trial was waterlogged twice at about anthesis (January-February, 2007) when 68% of the season's rain was received at the site. Genetic correlation of GY between the optimal and low N conditions at GV was 0.458.

Table 4.14: Heritability of GY and some secondary traits of TCs under Low N and Optimal conditions at Golden Valley.

Trait	Low N conditions	Optimal conditions
Grain yield	0.38 ± 0.87	0.32 ± 0.90
Anthesis-silking Interval	0.56 ± 0.78	-0.37 ± 1.10
Tassel size	0.56 ± 0.78	0.62 ± 0.74
Leaf senescence	0.02 ± 0.87	0.31 ± 0.91
Number of ears per plant	0.30 ± 0.91	0.17 ± 0.95
Leaf rolling	0.23 ± 0.93	-
Grain texture	0.33 ± 0.89	0.46 ± 0.84

4.4 Discussion

4.4.1 Genotype x environment interaction effects (GE) under low N

The results showed that genotypes evaluated during the three seasons (2004/05, 2005/06 and 2006/07) were significantly different. This meant that the genotypes could be discriminated from each other during each season of evaluation, and superior performers selected for further improvement. The two sites used in evaluating TCs in season 3 (GV and Kabwe) were also significantly different implying that, although both sites had been depleted of N, they were different. According to soil analysis (Table 4.2), the two trial sites differed in soil type and amount of rainfall received which probably affected varietal performance at the two sites. While soils at GV were sandy clay loamy, those at Kabwe were sandy loam. The two probably differed in retention of nutrients and water in the soil. According to Hongbotn (1974) the soils at Kabwe were drained of nutrients. Golden Valley received about 100mm more rainfall than at Kabwe and the heavier soils at the site probably retained more water and nutrients for the growing plants than at Kabwe.

The best four genotypes in GY under low N conditions were TC77, TC72, TC28 and TC53 progenies of LR40, LR35, LR76 and LR84, respectively, (Table 4.7) revealing the genetic potential of the LRs for GY under the N stress. None of the checks was among the top 10 highest yielding genotypes at the two sites. Superiority in tolerance of a genotype under low N conditions was also estimated based on average rank of selection indices at the two sites. It was found that TC28, TC49, TC72 and TC56 progenies of LR76, LR84, LR35, and LR84 were the most tolerant to low N at the two sites. Further, all the four highest yielding genotypes at the two sites were also among the 10 most tolerant genotypes to Low N. Therefore, the most tolerant genotypes to low N conditions were appropriate for cultivation in both areas and their respective S_1 lines as well as landraces (LR76, LR84, LR35, LR40 and LR11) should be used as base germplasm in breeding for the abiotic stress tolerance (Table 4.9). A released hybrid, MM603, was the best check and among the top 10 genotypes under low N conditions. This finding means that the hybrid should be a preferred variety for cultivation by resource poor farmers in agro-ecological Region II where both trials were located. However, MMV400, Pool16 and MMV600 were among the 10 genotypes with lowest tolerance to low N and will fail farmers who did not apply adequate N fertiliser. These results were consistent with those of Chapter 3 of this study.

4.4.2 Performance of landraces

The results showed that some LRs achieved higher GY than checks under low N conditions. LR49 had the highest yield of 2.67t ha^{-1} which was greater than the best check (ZM421). LR49, LR4, LR79 and LR93 were found to be the highest yielding genotypes under low N conditions, and were considered as low N tolerant. However, GY has low H^2 under low N conditions (Banziger and Lafitte, 1997) which limited its sole use in selecting superior genotypes under the stress, and selection index (SI) was preferred because it summarizes the worth of a genotype using information from other relevant traits (Banziger et al., 2000). It this study heritability of GY at GV was slightly higher under low N than under optimal conditions. This was due to water logging especially in the optimal trial which was on heavier soil than the low N trials.

Some LRs tolerated low N stress more than the checks. Of the top 10 genotypes in tolerance to low N, only one was a check (ZM421) and it ranked 8th. Landraces LR49, LR4, LR79 and LR93 (in that order) were the four most tolerant genotypes to low N stress. These should be used in developing low N tolerant varieties in Zambia.

4.4.3 Performance Per Se of S_1 Lines

Crossing of S_1 lines to a tester identified the S_1 lines that combined well with it. The tester had alleles that complemented superior S_1 lines under low N by combining well with them. Such materials (LR or S_1 lines) are important germplasm for use in developing improved varieties targeting the low N environment. Evaluation of the S_1 lines under low N conditions did not only aid in identifying those that were superior under low N conditions, but also in selecting against materials with unwanted traits. The most tolerant genotypes to low N stress were S_1 lines 80 (progeny of LR11) and 11 (progeny of LR38). The check (ZM521) was third but was highest in GY. The superiority of the two S_1 lines derived from the landrace meant the S_1 and by inference their respective LRs, had inherent ability to tolerate low N.

Of the top 10 genotypes, only one was derived from the top 10 LRs in tolerance to low N. Low tolerance to low N stress by the majority of S_1 lines derived from LRs which were among the best 10 under the abiotic stress could have been as a result of selfing that was carried out in the nursery. Selfing affects every locus and reduces both fertility and fitness (Falconer and Mackay, 1996). This probably affected the S_1 lines, hence their general lower performance than the check. Selfing reduced heterozygosity by one half and increased the frequency of dominance and recessive homozygotes at each selfing generation. However, allele frequency in the population does not change but assemblage of genes into genotypes changes (Falconer and Mackay, 1996). Therefore progenies of selfing were not likely to perform the same as their respective parents. Another benefit of selfing to breeding is the exposure of deleterious alleles that are exposed in heterozygous individuals and selected against, thereby improving the breeding materials. Further selfing in unselected germplasm can cause severe inbreeding depression as homozygosity of rare recessive alleles increase (Falconer, 1981). However, crossing of such inbred materials restores hybrid vigour (heterosis) where the progeny performs better than its parents. Superiority of some S_1 lines under low N conditions (Table 4.5) shows that inherent ability for tolerating the abiotic stress existed in them and can be used in crop improvement targeting low N environments.

4.4.4 Performance of testcrosses under low N conditions

4.4.4.1 Grain yield under low N conditions

The results showed that some TCs yielded higher under low N conditions than the checks. The top 10 genotypes in GY at GV and Kabwe were all TCs. The four highest yielding genotypes under low N conditions across the sites were TC77, TC72, TC28 and TC53 which were progenies of LR40, LR35, LR76 and LR84, respectively. The findings meant that the TCs and by inference their respective S_1 lines and LRs had superior GY potential over the checks under low N conditions and were therefore tolerant to the stress. Good performance of TCs may also be the result of good heterosis and implies that developing hybrids for low N envronment could be effective.

The results also show that TCs were not only superior to checks in GY under low N but under optimal conditions as well. Evaluation of TCs under low N and optimal conditions at GV revealed that all the 26 highest yielding genotypes at GV were TCs, while under optimal conditions the best check was ranked 4th and all other genotypes among the top 21 were TCs. Further, among the top 10 genotypes under optimal conditions were two testcrosses, TC51 and TC52, which were progenies of LR84 that contributed four TCs among the top 10 genotypes under low N conditions. This implies that LR84 had inherent ability for performance under both low N and optimal conditions. For the reason that farmers cultivate maize under varying soil fertility levels, high yield under low N and optimal conditions is desirable and LR84 is an appropriate germplasm in developing such a variety.

4.4.4.2 Tolerance to low N by testcrossses

Low N tolerant index (LNTI) was calculated as GY reduction under low N conditions in comparison to that under optimal conditions. It ranged from -254 to 88% among the genotypes. Rosielle and Hamblin (1981) observed that selection for stress tolerance was equivalent to selection for low yield reduction between the stress and non-stress environments. Later, Banziger and Lafitte (1997) found that where yield reductions were greater than 40%, direct selection under low N conditions was effective. Genotypes that reduced GY under low N conditions were considered as those affected by the stress and those that either maintained or increased GY under low N conditions as tolerant to the stress. It was found that 16 genotypes were tolerant to low N and among them was one check (Pool16) that ranked 4th in LNTI. Therefore, TC16, TC54, TC10 and TC56 were found to be the four best tescrosses in LNTI. Testcrosses TC16 and TC10 were derived from LR86, while TC54 and TC56 were from LR84. Earlier, it was reported that LR84 was also found to be superior in GY under low N and optimal conditions. These results mean that LR84 and LR86 exhibited tolerance to low N by yielding high under the stress.

When the best genotypes in tolerance to low N were evaluated for GY, it was found that seven of the 10 highest yielding genotypes were also found among the 10 most superior genotypes in tolerance to low N using the selection index. The four highest yielding genotypes based on average rank; TC77, TC72, TC28 and TC53 progenies of LR40, LR35, LR76 and LR84, respectively, were all among the top eight genotypes in tolerance to low N. Based on information included in calculating a selection index, the best yielding genotypes should be identified and these results generally showed this. However, differences in the ranking of genotypes using GY and SI is a matter of concern as high yielding genotypes can still be selected against. For example, a selection intensity of 5% could have failed to select TC77 and TC53 as they ranked 7th and 8th (of 100 genotypes) in tolerance to the stress. Similarly, at the same selection intensity, all the highest yielding TCs were not selected based on LNTI. All the highest yielding TCs can only be selected at 41% selection intensity when selection is based on LNTI. These results meant that selection of superior genotypes under low N conditions needs improvement. However, differences in the ranking of the genotypes in GY and in tolerance to low N also indicated that there was genetic variation in the genotypes that could be exploited to develop high yielding varieties.

The poor correspondence between LNTI and the SI probably also reflects problems of water-logging in the optimum trial rather than that of selection for low N tolerance. Errors for differences between means are always larger than for individual means, which also contributes to the variability in LNTI estimates. The study found that the mean of the selected TCs were above trial mean for GY, EPP, Tsize, days to mid-anthesis and plant height at both GV and Kabwe. Similarly, the selected TCs had below trial mean values for ASI, Lsene and Gtext at the two sites. The selected genotypes had above trial mean value for Lroll at GV and below trial mean value achieved at Kabwe. These results generally show that the genotypes selected were high yielding and were superior in tolerance to low N stress.

The study found that all the top 10 genotypes under low N at Kabwe and five of the top 10 genotypes under low N conditions at GV were progenies of LRs that were among the top 10 in drought tolerance during the 2004/05 season. This meant that selecting for drought tolerance also improved tolerance to low N. This was in agreement with Lafitte and Banziger (1997) who achieved a 3.4% GY increase per year under low N conditions following selection under drought conditions. Achieving tolerance of both stresses in a variety was appropriate for most small-scale farmers in Regions I and II where both stresses limited maize production.

4.4.5 General Combining Ability effects of S_1 lines

General combining ability effects estimated how S_1 lines combine with the tester. Since only one tester was used, genotypes that combined well with the tester also yielded higher than those that did not. Therefore, genotypes obtained similar ranking in GCA effects and in GY. All the 10 highest yielding TCs under low N conditions had significant GCA effects for GY. The findings meant that the respective S_1 lines combined well with the tester and were superior under low N stress. Significant GCA effects meant that use of the genotypes in population improvement under low N was effective. Therefore, testcrosses TC56, TC72, TC7 and TC37, and by inferences, respective S_1 lines and LRs were selected as the most tolerant genotypes to low N stress based on GCA effects. All the 10 highest yielding genotypes under low N had positive GCA effects in GY, implying that additive gene action conditioned them under the stress. The findings were in agreement with Omoiui et al. (2007) who reviewed inheritance studies of maize under low N conditions. However, Betran et al. (2003) had earlier found that non-additive gene action was important among inbred lines and hybrids under low N conditions.

4.4.6 Heritability and genetic correlation of secondary traits with grain yield

To measure the extent to which the traits were determined by genotypes, broad sense heritability (H^2) was calculated. It was found that H^2 for GY was 0.38 under low N conditions, and was higher than that for Lsene, Lroll, EPP and Gtext, but was lower than that for ASI (0.56) and Tsize (0.56). The results meant that much of the GY was not determined by genotypic effects suggesting that selection based on GY alone under low N conditions was not effective. Sibale and Smith (1997) in studying the relationship between traits and GY of maize under low N conditions in Malawi, also found similar H^2

estimate (0.41). Banziger and Lafitte (1997) reported that H^2 for ASI was 0.52 and were in agreement with these results. However, although high H^2 of Tsize was found, its correlation with GY was low (r = 0.210*) and may not be effective in identifying high yielding genotypes that tolerated the low N stress. It was also found that much of the GY, Lsene, Lroll, EPP and Gtext was environmental which weakened their efficiency in selecting genotypes under low N conditions. However, Lsene, EPP, Tsize and Gtext had significant correlation with GY. Therefore, selecting large Tsize could be effective in identifying superior genotypes under low N conditions when its correlation with GY was high. This implies that its use should not be generalized but restricted to germplasm whose Tsize and GY correlated highly. The recommendation was at variance with earlier findings (Banziger et al., 2000) who did not list Tsize as one of the secondary traits in identifying superior genotypes under low N conditions. Probably, these findings are particularly relevant to unimproved germplasm which was used in the study.

Indirect selection under optimal environment was considered to select genotypes that could yield well under Low N conditions. Importance of indirectly selecting for GY under optimal conditions, for the low N environment, depended on the genetic correlation of GY under optimal to that under low N conditions. Genetic correlation (r_G) expresses the extent to which two measurements reflect the character that is genetically the same (Falconer, 1981). Grain yield genetic correlation between the low N and optimal environments was found to be 0.458. The moderate correlation meant that genotypes selected for GY in one environment may not express their superiority under the other environment. Banziger et al. (1997) also found positive genetic correlations of GY between low and optimal conditions which decreased with increasing LNTI under low N conditions, indicating importance of specific adaptability of genotypes.

4.4.7 Selection of genotypes tolerant to low N

Banziger et al. (2000) reported that information on GY, EPP, ASI and Lsene should be used in selecting genotypes that tolerate low N. In this study, GY, ASI, EPP, Tsize, Lsene, Lroll, and Gtext were evaluated for their relevance in identifying maize genotypes tolerant under low N conditions. Since small-scale farmers selected their seeds mainly based on superiority in grain flintiness (Chapter 2), its evaluation assessed effectiveness of farmer selection in the study areas.

Significant correlations of GY with EPP (moderate, r = 0.551*), Gtext (weak, r = -0.233*), Lsene (weak, r = 0.199*) and Tsize (weak, r = 0.21*) were found implying that respective traits weakly explained GY. Comparatively, Banziger and Lafitte 1997) found strong correlations of GY with EPP (r = 0.78, high) and r = 0.42 (moderate) for Lsene. The results showed that Lsene should be weighed less than EPP in calculating selection indices. Negative correlation of GY with ASI (weak, r = -0.092) and Gtext (r= -0.233*) under low N conditions were found implying that they had little role in selections in this trial. Their values reduced as GY increased and were in agreement with Banziger and Lafitte (1997) for ASI. A negative correlation of GY and Gtext meant that when farmers selected their seed based on increased grain texture (flint), they also selected for low GY. It implied that farmer selection that emphasized selecting for flintiness (Chapter 2) did not help increase GY of the LRs. The number of ears per plant, Tsize and Lsene had positive correlation with GY meaning that an increase in the respective trait also indicated increased GY.

The magnitude of the correlation explained the trait's association with yield. It was found that EPP had stronger positive correlation than Tsize whose correlation was stronger than that of Lsene. Grain texture also had stronger negative correlation with GY than ASI. A trait that had stronger significant correlation with GY provided more information in estimating GY. Therefore, based on these results, the traits were listed in order of their strength in correlating with GY, as follows; EPP, Gtext, Tsize, Lsene, ASI and Lroll. Considering that Tsize had higher H^2 than EPP and Gtext, its use in selecting genotypes under low N conditions could be effective. However, the recommendation to select for increasing Tsize is at variance with other studies that have found that large tassels reduced GY, either physiologically by competition for photosynthates or physically by a shading effect (Grogan, 1956; Hunter et al., 1969; Mock and Schuetz, 1974). Magorokosho and Pixley (1997) measured Tsize on a scale 1 (small) to 5 (large) while Banziger et al. (2000) reported that Tsize may be measured based on the number of tassel branches or on small to large visual scale. In this study, tassel branch numbers were used to estimate its size. However, a tassel with more branches is not necessarily big in size or a larger producer of pollen than one with few branches, although branch number is positively correlated with tassel dry weight.

4.5 Conclusions and Implications to breeding

The study determined a) tolerance to low N, b) genotype x environment interaction effects; c) heritability of traits and; d) correlations of traits of maize genotypes under low N conditions. It has been found that some maize LRs tolerated the stress caused by low N more than improved maize varieties. The 10 most tolerant LRs for low N conditions were: LR49, LR,4, LR79, LR93, LR69, LR19, LR1, LR28, LR11 and LR10 (in that order). It was also found that the best 10 S_1 lines under low N conditions were: 193, 11, 28, 68, 13, 109, 127, 25, 135 and 35. Superior testcrosses under low N were as follows:

Testcross	**S_1 line**	**Landrace**	**Region sampled from**
TC56	136	LR84	III
TC32	72	LR11	I
TC39	104	LR93	II
TC72	171	LR35	II
TC7	14	LR38	II
TC19	38	LR 86	II
TC49	127	LR 84	III
TC28	54	LR 76	II
TC27	53	LR 76	II
TC77	184	LR 40	II

Most of the testcrosses tolerant to low N stress were sampled from Region II implying that the area was a good source for germplasm targeting low N conditions in Zambia. Landraces LR84 and LR76 contributed two testcrosses each among the 10 best TCs under low N conditions revealing their genetic potential for tolerance to the stress.

Eight of the most tolerant TCs to low N stress were progenies of the same parents that contributed eight TCs that were among the top 10 TCs under drought conditions. These include LR11, LR35, LR38, LR76, LR84 and L86. These genotypes should be used to develop varieties for tolerance to both the low N and drought stress. These results support the notion that the underlying mechanisms for low N and drought tolerance are similar. A variety that tolerates drought and low N is appropriate, especially for small-scale farmers in Regions I and II where both stresses limit maize production.

The genetic correlation of GY between the low N and optimal environments was moderate (0.458) and meant that indirect selection for low N tolerance under optimal conditions would not be very effective. Heritability of GY was low (0.38) meaning that basing selection on GY alone under Low N conditions was not effective as environment played a large part in its expression. Therefore, discrimination of genotypes based on GY alone was not effective. This meant that secondary traits should be used to supplement GY to identify superior genotypes under low N conditions. Grain yield, Tsize and EPP should be used in calculating selection indices to identify genotypes that tolerate low N.

It has therefore been found that there was adequate genotypic variation for low N tolerance among maize LRs which can be improved by selection. Landraces, S_1 lines and TCs derived from landraces superior in tolerance to low N were identified. These should be used as germplasm in developing high yielding varieties targeting low N and dry environments.

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Appendices

Appendix 4.1: Germplasm supplied by CIMMYT for the study

Entry	Stock ID	Material	Origin
LR1	Z003	Kafwamba	Zambia-Kafue
LR2	Z006	Gankata 3	Zambia-Mazabuka
LR3	Z009	Local (Eastern Province)	Zambia-Monze
LR4	Z010	Mapopgwe a Chitonga	Zambia-Monze
LR5	Z 011	Hickory King	Zambia-Gwembe
LR6	Z012	8-line	Zambia-Choma
LR7	Z014	Local	Zambia-Choma
LR8	Z016	Local	Zambia-Choma
LR9	Z019	Gankata	Zambia-Kalomo
LR10	Z020	Kazungula	Zambia-Kazungula
LR11	Z 021	Sesheke	Zambia-Sesheke
LR12	Z 022	Silozi	Zambia-Sesheke
LR13	Z024	Kangalingali	Zambia-Sesheke
LR14	Z027	Mboni ya Sintu	Zambia-Kaoma
LR15	Z028	Katiko	Zambia-Kaoma
LR16	Z029	Mboni ya Sintu	Zambia-Kaoma
LR17	Z030	Nyamavhunga	Zambia-Lukulu
LR18	Z031	Mundele wa Chintu	Zambia-Lukulu
LR19	Z032	Local	Zambia-Lukulu
LR20	Z033	Mboni ya Sintu	Zambia-Kabompo
LR21	Z034	Mun’indo	Zambia-Zambezi
LR22	Z035	Local	Zambia-Zambezi
LR23	Z036	Mundele wa Chintu	Zambia-Kabompo
LR24	Z038	Yellow Maize	Zambia-Kabompo
LR25	Z039	Kahilahila	Zambia-Kabompo
LR26	Z 041	Kabaka 1	Zambia-Mufumbwe
LR27	Z044	Local	Zambia-Mufumbwe
LR28	Z045	Mboni ya Sintu	Zambia-Mufumbwe
LR29	Z046	Local	Zambia-Mufumbwe
LR30	Z047	Kapira 1	Zambia-Solwezi
LR31	Z050	Local	Zambia-Solwezi
LR32	Z051	Local	Zambia-Chingola
LR33	Z054	Kanjilimane 3	Zambia-Masaiti
LR34	Z056	local	Zambia-Masaiti
LR35	Z 057	Local	Zambia-Kapiri Mposhi
LR36	Z058	Gankata	Zambia-Mkushi
LR37	Z060	Chilala	Zambia-Mkushi
LR38	Z 061	Chilala	Zambia-Mkushi
LR39	Z062	Chilala 8-Row	Zambia-Serenje
LR40	Z 116	Pop25-#	Zambia-Lusaka
LR41	Z064	Chilala	Zambia-Serenje
LR42	Z066	Kanjele	Zambia-Serenje

Entry	Stock ID	Material	Origin
LR43	Z068	Karimwa	Zambia-Mpika
LR44	Z069	Pandama	Zambia-Mpika
LR45	Z070	Karimina	Zambia-Kasama
LR46	Z071	Kalimwa	Zambia-Kasama
LR47	Z072	Kalimwa	Zambia-Mporokoso
LR48	Z073	Kalimwa Yellow	Zambia-Luwingu
LR49	Z 074	Kalimwa Red Stripped	Zambia-Luwingu
LR50	Z075	Kalimwa (HK)	Zambia-Luwingu
LR51	ZO78	Karimwa	Zambia-Mbala
LR52	Z079	Kandimwa	Zambia-Mpulungu
LR53	Z081	Chimambwe	Zambia-Mbala
LR54	Z082	Chimambwe/Kalimwa	Zambia-Mbala
LR55	Z083	Mofati	Zambia-Nakonde
LR56	Z084	Avxansi	Zambia-Isoka
LR57	Z085	Mofati	Zambia-Isoka
LR58	Z086	Pandawe	Zambia-Isoka
LR59	Z087	Pandawe	Zambia-Isoka
LR60	Z088	Masika	Zambia-Lundazi
LR61	Z093	Local	Zambia-Lundazi
LR62	Z117	Pop10	Zambia-Lusaka
LR63	Z097	Local	Zambia-Lundazi
LR64	Z098	Chamakolo	Zambia-Chipata
LR65	Z100	Kenya	Zambia-Petauke
LR66	Z101	Chibahwe	Zambia-Petauke
LR67	Z102	Vinchewele	Zambia-Petauke
LR68	Z103	Senga	Zambia-Nyimba
LR69	Z104	Senga	Zambia-Nyimba
LR70	Z105	Yachishi	Zambia-Chongwe
LR71	Z106	Gankata	Zambia-Chongwe
LR72	Z107	Gankata 8-lines	Zambia-Mumbwa
LR73	Z108	Gankata Flint	Zambia-Mumbwa
LR74	Z 109	Kafuamba	Zambia-Chibombo
LR75	Z110	Gankata	Zambia-Mazabuka
LR76	Z 111	Gankata 10-lines	Zambia-Mazabuka
LR77	A1093-95	Gankata 2-#	Zambia-Mazabuka
LR78	A1093-96	Gankata 4-#	Zambia-Mazabuka
LR79	A1093-97	Siampungani-#	Zambia-Monze
LR80	A1093-98	Mboni ya Silozi	Zambia-Senanga
LR81	A1093-99	90-Days-#	Zambia-Kabompo
LR82	A1093-100	Kahilahila	Zambia-Kabompo
LR83	A1093-101	Kabaka 2-#	Zambia-Mufumbwe
LR84	A1093-102	Kanjilimane1-#	Zambia-Kitwe
LR85	A1093-103	Kanjilimane2-#	Zambia-Kitwe
LR86	A1093-104	Local-#	Zambia-Mpongwe

Entry	Stock ID	Material	Origin
LR87	A1093-105	Gankata Red-#	Zambia-Mkushi
LR88	A1093-107	Akansalika-#	Zambia-Serenje
LR89	A1093-108	Kalimwa (Red)-#	Zambia-Luwingu
LR90	A1093-109	Chimambwe-#	Zambia-Mbala
LR91	A1093-110	Kafula-#	Zambia-Chama
LR92	A1093-111	Kanjerenjere-#	Zambia-Chama
LR93	A1093-112	Pool16-#	Zambia-Chama
LR94	A1093-113	Local-#	Zambia-Chama
LR95	A1093-114	Kanjere-#	Zambia-Lundazi
LR96	A1093-115	Kafwamba-#	Zambia-Mazabuka
97	Z114	Pool16	Zambia-Mt. Makulu
98	A1049	ZM421-FLINT	HA04A-ART ISO 5
99	A1045	ZM521	HA04A-ART ISO 3
100	A1035	ZM623	HA04A-ART-CIMMYT
Tester	-	CML312/CML395	CIMMYT

Appendix 4.2: Testcrosses (TCs) and checks evaluated in season 3

Entry	Variety Name	Pedigree	LR	Meterial	Origin
TC1	ZL38S-6T-1	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC2	ZL38S-7T-2	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC3	ZL38S-10T-3	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC4	ZL38S-11T-4	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC5	ZL38S-12T-5	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC6	ZL38S-13T-6	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC7	ZL38S-14T-7	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC8	ZL40S-07T-8	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC9	ZL26S-14T-9	LR26-S_1x(CML312/CML395)	26	Kabaka 1	Mufumbwe
TC10	ZL86S-01T-10	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC11	ZL86S-02T-11	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC12	ZL86S-03T-12	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC13	ZL86S-04T-13	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC14	ZL86S-05T-14	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC15	ZL21S-13T-15	LR21-S_1x(CML312/CML395)	21	Mun'indo	Zambezi
TC16	ZL86S-07T-16	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC17	ZL86S-08T-17	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC18	ZL86S-09T-18	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC19	ZL86S-10T-19	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC20	ZL86S-11T-20	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC21	ZL86S-12T-21	LR86-S_1x(CML312/CML395)	86	Local-#	Mpongwe
TC22	ZL76S-03T-22	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC23	ZL76S-04T-23	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC24	ZL76S-05T-24	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC25	ZL76S-07T-25	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC26	ZL76S-09T-26	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC27	ZL76S-11T-27	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC28	ZL76S-12T-28	LR76-S_1x(CML312/CML395)	76	Gankata 10 lines	Mazabuka
TC29	ZL21S-05T-29	LR21-S_1x(CML312/CML395)	21	Mun'indo	Zambezi
TC30	ZL21S-09T-30	LR21-S_1x(CML312/CML395)	21	Mun'indo	Zambezi
TC31	ZL21S-12T-31	LR21-S_1x(CML312/CML395)	21	Mun'indo	Zambezi
TC32	ZL11S-02T-32	LR11-S_1x(CML312/CML395)	11	Sesheke	Sesheke
TC33	ZL11S-03T-33	LR11-S_1x(CML312/CML395)	11	Sesheke	Sesheke
TC34	ZL12S-01T-34	LR12-S_1x(CML312/CML395)	12	Silozi	Sesheke
TC35	ZL12S-05T-35	LR12-S_1x(CML312/CML395)	12	Silozi	Sesheke
TC36	ZL12S-09T-36	LR12-S_1x(CML312/CML395)	12	Silozi	Sesheke
TC37	ZL12S-10T-37	LR12-S_1x(CML312/CML395)	12	Silozi	Sesheke
TC38	ZL12S-11T-38	LR12-S_1x(CML312/CML395)	12	Silozi	Sesheke
TC39	ZL93S-05T-39	LR93-S_1x(CML312/CML395)	93	Pop 16-#	Chama
TC40	ZL93S-07T-40	LR93-S_1x(CML312/CML395)	93	Pop 16-#	Chama
TC41	ZL93S-09T-41	LR93-S_1x(CML312/CML395)	93	Pop 16-#	Chama
TC42	ZL93S-11T-42	LR93-S_1x(CML312/CML395)	93	Pop 16-#	Chama
TC43	ZL93S-12T-43	LR93-S_1x(CML312/CML395)	93	Pop 16-#	Chama
TC44	ZL74S-03T-44	LR74-S_1x(CML312/CML395)	74	Kafuamba	Choma
TC45	ZL74S-05T-45	LR74-S_1x(CML312/CML395)	74	Kafuamba	Choma

Entry	Variety Name	Pedigree	LR	Meterial	Origin
TC46	ZL74S-12T-46	LR74-S_1x(CML312/CML395)	74	Kafuamba	Choma
TC47	ZL38S-08T-47	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC48	ZL74S-14T-48	LR74-S_1x(CML312/CML395)	74	Kafuamba	Choma
TC49	ZL84S-01T-49	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC50	ZL84S-02T-50	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC51	ZL84S-03T-51	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC52	ZL84S-04T-52	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC53	ZL84S-06T-53	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC54	ZL84S-08T-54	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC55	ZL84S-09T-55	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC56	ZL84S-10T-56	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC57	ZL84S-12T-57	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC58	ZL84S-13T-58	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC59	ZL84S-14T-59	LR84-S_1x(CML312/CML395)	84	Kanjilimane 1-#	Kitwe
TC60	ZL85S-02T-60	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC61	ZL85S-03T-61	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC62	ZL85S-05T-62	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC63	ZL85S-10T-63	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC64	ZL85S-11T-64	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC65	ZL85S-12T-65	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC66	ZL85S-13T-66	LR85-S_1x(CML312/CML395)	85	Kanjilimane 2-#	Kitwe
TC67	ZL05S-01T-67	LR5-S_1x(CML312/CML395)	5	Hickory King	Gwembe
TC68	ZL38S-09T-68	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC69	ZL38S-01T-69	LR38-S_1x(CML312/CML395)	38	Chilala	Mkushi
TC70	ZL35S-01T-70	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
71 (c)	Landrace	Landrace – check	Check	Local	Chibombo
TC72	ZL35S-03T-72	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
TC73	ZL35S-06T-73	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
TC74	ZL35S-10T-74	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
TC75	ZL35S-12T-75	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
76(c)	Pop25	Pop25 - check		Improved	
TC77	ZL40S-02T-76	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC78	ZL40S-03T-77	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC79	ZL40S-04T-78	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC80	ZL40S-05T-79	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC81	ZL40S-06T-80	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
82(c)	MMV600	MMV600 – check		Improved	
TC83	ZL40S-11T-81	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC84	ZL40S-12T-82	LR40-S_1x(CML312/CML395)	40	Pop 25	Chipata
TC85	ZL79S-01T-83	LR79-S_1x(CML312/CML395)	79	Siampungani	Monze
TC86	ZL79S-02T-84	LR79-S_1x(CML312/CML395)	79	Siampungani	Monze
87(c)	Pool16	Pool16 – check		Improved	
TC88	ZL79S-14T-85	LR79-S_1x(CML312/CML395)	79	Siampungani	Monze
TC89	ZL35S-07T-86	LR35-S_1x(CML312/CML395)	35	Local	K/Mposhi
TC90	ZL49S-08T-87	LR49-S_1x(CML312/CML395)	49	Kalimwa R Stripped	Luwingu
TC91	ZL49S-09T-88	LR49-S_1x(CML312/CML395)	49	Kalimwa R Stripped	Luwingu
TC92	ZL49S-10T-89	LR49-S_1x(CML312/CML395)	49	Kalimwa R Stripped	Luwingu
93(c)	SC403	SC403 – check		Improved	
94(c)	MM603	MM603 – check		Improved	

Entry	Variety Name	Pedigree	LR	Meterial	Origin
95(c)	MRI724	MRI724 – check		Improved	
96(c)	Tester	Tester – check		Improved	
97(c)	ZM421	ZM421 – check		Improved	
98(c)	ZM521	ZM521 – check		Improved	
99(c)	ZM621	ZM621 – check		Improved	
100(c)	MMV400	MMV400 – check		Improved	

Chapter 5: S_1 selection of local maize landraces for drought tolerance

Abstract

Drought is one of the most important constraining factors to maize production in Zambia. In this study, S_1 selection was used to select for drought tolerance from local landraces during 2004-2007 in Zambia. Ninety-six landraces were evaluated for grain yield (GY) and secondary traits under drought, low nitrogen (N) and optimal conditions. At the same time, the landraces were selfed in a nursery under optimal conditions to generate S_1 lines. Data on GY, anthesis-silking interval (ASI), number of ears per plant (EPP), leaf senescence (Lsene), leaf rolling (Lroll) and tassel size (Tsize) was used to calculate selection indices. Fourteen S_1 lines from each of the best four landraces under drought, low N, optimal conditions and across the selection conditions were selected for evaluation under the three selection conditions. They were also crossed onto a single cross hybrid tester in a nursery under optimal conditions. Twenty-two best S_1 lines under low N, drought, optimal conditions and across the three selection environments were identified and their respective testcrosses selected for evaluation under the three selection environments. General combining ability (GCA) effects, broad sense heritability estimates (H^2) and genetic correlation (r_G) for GY were calculated. High yielding genotypes had positive GCA effects for GY under drought meaning that population improvement was effective under drought. The heritability estimate for GY was low (0.17) implying that selection based on GY alone was not effective but that in addition, secondary traits should be used. The r_G for GY under low N and optimal environments was low (0.03) suggesting that genotypes selected for GY under optimal conditions could perform poorly under drought. Use of a selection index across environments and traits is preferred, and weighting of secondary traits based on phenotypic correlations is discussed. The study found that landraces Siampungani-#, Silozi, Gankata 10 lines and Kanjilimane1-# were most tolerant to drought and should be used to develop drought tolerant varieties.

Key words: Maize, landrace, heritability, correlation, drought, tolerance, stress

5.1 Introduction

Drought occurs when there is insufficient moisture in the soil to meet the needs of a crop at a particular time. It is one of the most important constraining factors to maize production in drought prone areas of agro-ecological Regions I and II of Zambia. During the growing season drought is experienced for a period of about 42-62% of the rain season in Region I and from 25-33% of the rain season in Region II (Bunyolo et al., 1997). The problem of drought is wide spread among small-scale farmers not only in Zambia but in the whole southern African region (Waddington and Heisey, 1997). Yield losses as a result of drought are estimated at 10-50% in southern Africa (Zambezi and Mwambula, 1997). Machida (1997) reported yield losses of about 68% among small-scale communal farmers in Zimbabwe, while Logrono and Lothrop (1997) reported yield losses of up to 75% in Asia.

Although a maize plant requires an adequate amount of moisture throughout its growing season, it is most susceptible to stress at anthesis when reproductive processes responsible for kernel set are occurring (Bosch et al., 2004). Plants under drought stress become dehydrated thereby inhibiting photosynthesis, reducing the carbohydrate stream and lowering invertase activities in the ovaries (Zinselmeier et al., 2000). In the absence of carbohydrates from the parent, the starch pool in the developing seed is depleted and abortion ensues, seed set is decreased. The maize plant generally responds by slowing down ear growth in relation to tassel growth and the anthesis-silking interval (ASI) increases (Parsons, 1982). After flowering, water content of the grain decreases as dry matter deposition occurs and grain fills. During this time the maintenance of a high proportion of green active leaves is important.

Plant efficiency can be measured by its ability to allocate most of the photosynthates produced toward the formation of grain (Guei and Wassom, 1996) and is reflected in the harvest index (HI). HI is the ratio of grain to total aboveground biomass and is high under drought among tropical germplasm (Moser et al., 1997). Traits which indicate a greater partitioning of assimilate supply to the growing ear at flowering such as small tassels are indicative of genotypes with high HI (Edmeades et al., 1997). Maize produces pollen excessively with 25000 to 50000 pollen grains produced for each potential kernel (Fischer and Palmer, 1984). An increase in grain yield (GY) as a result of a reduction in tassel size (Tsize) increases HI of the plant. When under drought, turgor is lost, and a maize leaf rolls in order to reduce radiation load on the leaf. This reduces its usage of water which is one indication of a genotype's ability to mitigate the stress (Mohr and Dickson, 1979). The ability of a plant to produce at least one ear per plant under drought indicates tolerance to the stress. In general, a genotype that limits its vital functions to ensure kernel development during water deficiency exhibits drought tolerance (Ehlers and Goss, 2003).

The growth of maize under drought is interplay between the genotype and the environment under which it grows (Christiansen and Lewis, 1982). When genotypes respond differently across environments, genotype x environment interaction (GE) is said to occur (Fox et al., 1997). This means that the best genotype under one level of drought stress is not the best in another (Falconer, 1981). Where GE is not significant, varietal means across environments are adequate indicators of genotypic performance. Significant GE means that selections from one environment may not perform well in another, and attempts should be made to find an environment that best fits such a genotype. Information on GE enables a breeder to employ an appropriate breeding strategy for either specific or wide adaptation (Romagosa and Fox, 1993).

Rosielle and Hamblin (1981) defined selection for stress tolerance as selection for low yield depression. Given y_1 = grain yield under optimal (non stress) conditions and y_2 = grain yield under drought, tolerance is defined as $y_3 = y_2 - y_{1.}$ It implies that ability to produce high yield under drought expresses tolerance to the stress. Parsons (1982) reported that recurrent selection under drought conditions increased GY of maize genotypes in drought stressed environments. Selection for drought tolerance was also reported to increase grain yield under low nitrogen (N) environments (Banziger et al., 1999). However, heritability of GY under drought is low and basing selection on it alone may not be effective (Byrne et al., 1995). Therefore, the use of secondary traits which are significantly correlated with yield, plus yield per se is advocated. Information of secondary traits may be used in calculating selection indices to identify genotypes that tolerated drought stress. A selection index summarizes the worth of a genotype using information from several traits. A good secondary trait is genetically associated with grain yield under stress and has high heritability (Banziger et al., 2000). Edmeades et al. (1999) considered effective use of secondary traits in a selection index in selecting for drought tolerance. They found information of ASI, EPP, Tsize, Lsene and Lroll effective is in selection index.

The mean performance of a line in all its crosses expressed as a deviation from the mean of all crosses expresses the general combining ability (GCA) of the line (Hallauer and Miranda, 1988). Significant GCA effects indicate additive gene action (Falconer, 1981) and can also be used to select superior genotypes under drought when genotypes are crossed to a known drought tolerant parent, or tester. The GCA effects are measured when the tester is heterogeneous and broad based (Hallauer and Miranda, 1988). High GCA effects for a trait reflect the presence of the desired drought tolerant alleles being sought. Vasal et al. (1992) crossed 88 inbred lines to four testers and used GCA and specific combining ability (SCA) effects to identify and form heterotic groups of maize with subtropical adaptation. In the current study, GCA effects were used to identify genotypes with traits for tolerance to drought.

Information on heritability, gene action, and correlations of various traits under drought will contribute to improving breeding strategies when selecting for drought tolerance. Beck and Willcox (1997) reported that additive gene action for GY under drought conditions was significant and, in agreement with Betran et al. (2003), suggested that selection would be effective in breeding for drought tolerance. Edmeades et al. (1999) and Banziger et al. (2000) found that information on GY, the number of ears per plant (EPP), ASI, leaf senescence (Lsene), leaf rolling (Lroll) and Tsize were important in selecting superior genotypes under drought. Chapter 2 of this study revealed that most small-scale farmers selected their seeds based on flintiness of grain texture (Gtext). Therefore, these traits were measured in the current study.

This study was carried out to determine: a) tolerance to drought; b) genotype x environment interaction effects; c) heritability and; e) correlations of selected traits of maize genotypes under drought. The hypothesis tested in the study was that there is adequate genetic variation among maize landraces (LRs) for drought tolerance that can be improved by selection.

5.2 Materials and methods

5.2.1 Germplasm, experimental environments and experimental designs

The Zambian landraces (LRs) used in the study are described in Chapter 4 (Appendix 4.1). The S_1 lines and testcrosses were generated as described under Chapter 4 (see 4.2.). The LRs, S_1 lines and TCs were evaluated under drought, low nitrogen (N) and optimal conditions as described in Chapter 4. Experimental designs used in evaluating LRs and S_1 lines were also described in Chapter 4 (see 4.2). Information on secondary traits and their weights when used for calculating selection indices under drought conditions was are as follows:

Trait	**Weight**	**Preference**
Grain yield	5	Increasing
Number of ears per plant	3	Increasing
Leaf senescence	-2	Reducing
Anthesis-silking interval	-2	Reducing
Tassel size	-2	Reducing
Leaf rolling	-1	Reducing

During the third season (2006/07), the 88 TCs and 12 checks (Appendix 4.2) were evaluated in performance trials under drought and optimal conditions at Lusitu and Luangwa. Water to the trial was applied using furrow irrigation which was withdrawn about a week before anthesis of the earliest entry based on amount of heat units the same took to flower during the earlier optimal trial in summer. Soil moisture level at the drought trials was monitored by measurements (volume of water per volume of soil) every 10d (at 300mm, 600mm and 900mm depth) by the Soil Physics Laboratory at ZARI (Table 5.1). Two irrigations were applied after the moisture withdrawal period (35 days from the previous irrigation). Detailed description of the managed drought stress protocol is presented by Banziger et al. (2000). The trial at Lusitu was about 200m away from the Zambezi River, while the other trial was about 5km from Luangwa.

Table 5.1: Percent soil moisture measured as volume (V) of water per V of soil at trial sites

Day	Remark	%V soil moisture at Lusitu			%V soil moisture at Luangwa		
0	Last irrigation	300mm	600mm	900mm	300mm	600mm	900m
5	1st soil test	14	12	12	26	23	18
15	2nd soil test	8	10	10	22	31	21
25	3rd soil test	8	10	8	25	23	25
35	4th soil test	12	17	16	16	12	14

The soil at Lusitu was up to 900mm deep and was a sandy loam. Its field capacity (FC) was 21% moisture on volumetric basis, permanent wilting point (PWP) was 9%. Drought was assumed at ≤ 15% moisture when half of the plant available water was depleted (Prichard, 2007). At Luangwa the soils up to 900mm depth were generally heavy clay and FC was 36%, PWP 17% and drought was assumed created at <26.5% (Banziger et al., 2000).

The trials were laid out as a 10 x 10 lattice design with two replications. The checks included seven popular OPVs, four popular hybrids and a landrace (LR). The plot size was one row, 5m long, 0.75m between rows, with two plants per hill spaced 0.5m within the row (22 plants per row; 22 plants per entry). The trials were maintained clean of weeds by hand weeding. Recording of main characteristics was as in Chapter 4 (section 4.2.3). Planting and harvesting were done by hand. Testcross data was analyzed in GenStat (Payne et al., 2007) as described in Chapter 4.

5.3 Results

5.3.1 Performance of genotypes

5.3.1.1 Performance of landraces

Landraces under evaluation were significantly different ($p \leq 0.05$) for GY under drought conditions. The highest yielding genotype under drought conditions was LR76 with 3.97t ha^{-1}, while the second was a check (ZM623) with 2.86t ha^{-1} (Table 5.2). Of the 10 highest yielding genotypes under drought conditions, eight were LRs while two were checks ranked 2nd and 10th (1.95t ha^{-1}). The other two checks were ZM421 which ranked 48th (1.05t ha^{-1}) and ZM521 that ranked 51st (0.98t ha^{-1}). All of the 10% lowest yielding genotypes under drought were LRs with yields ranging from 0.032 to 0.003t ha^{-1}. The lowest yielder under drought conditions was LR28. LR35 yielded highest (6.57t ha^{-1}) under optimal conditions but was not among the top 10 genotypes under drought conditions. All cultivars under optimal conditions yielded above the mean of cultivars under drought conditions. Only LR26 and LR76 were among the top 10 genotypes in GY under both drought and optimal conditions.

The most tolerant genotype to drought based on selection index (SI) was LR74 but it ranked 12th in GY. However, the highest yielding genotype (LR76) ranked 6th in SI, while the second highest yielder (ZM623) maintained its rank under SI. Landrace LR26 that ranked 4th in GY was 24th in SI while all the other 10 highest yielding genotypes under drought ranked below 19th in SI. Five of the genotypes ranked among the top 10 in GY were also among the top 10 in drought tolerance (Table 5.2). Only LR76 and LR86 were among the 10 most tolerant genotypes under drought conditions and among the top 10 genotypes in GY under optimal conditions.

Table 5.2: Ten of the highest and lowest yielding landraces under drought and optimal conditions

Performance under drought			Performance under optimal	
LR	GY (t ha^{-1})	LR based on SI	LR based on GY	GY (t ha^{-1})
Top 10				
LR76	3.97	LR74	LR35	6.57
ZM623 (c)	2.86	ZM623 (c)	ZM421 (c)	6.48
LR40	2.24	LR93	LR5	5.82
LR26	2.21	LR38	LR26	5.81
LR4	2.13	LR21	LR49	5.66
LR43	2.10	LR76	LR86	5.60
LR62	2.09	LR40	LR53	5.59
LR38	2.03	LR86	LR16	5.57
LR21	2.00	LR84	LR33	5.55
Pool16 (c)	1.95	LR58	LR76	5.48
Mean	2.36			5.81
Bottom 10				
LR71	0.32	LR70	LR29	2.55
LR87	0.28	ZM521 (c)	LR31	2.43
LR47	0.28	LR62	LR17	2.42
LR42	0.27	LR85	LR68	2.40
LR61	0.26	LR92	LR69	2.39
LR52	0.26	LR82	LR58	2.34
LR78	0.26	LR88	LR64	2.28
LR64	0.18	Pool16 (c)	LR62	2.22
LR36	0.14	LR83	LR88	2.15
LR28	0.003	LR90	LR67	1.36
Mean	0.22			2.25
Trial Statistics				
Max	3.97			6.57
Min	0.003			1.36
Mean	1.08			3.85
SE	± 0.52			± 1.30
LSD	1.03			2.57
P value	0.001			0.103

5.3.1.2 Performance of S_1 lines under drought and optimal conditions

The S_1 lines under evaluation were significantly different ($p \leq 0.05$) for GY under drought conditions. Grain yield of S_1 lines ranged from zero to 4.25t ha^{-1} (Table 5.3). All of the top 10 genotypes in grain yield were S_1 lines, while the check (ZM521) ranked 99th of the 225 entries and achieved GY of 1.79t ha^{-1}. The highest yielding genotype was S_1 line 187, a progeny of LR40. The 10 lowest yielding genotypes were all S_1 lines and achieved yields ranging from 0.18t ha^{-1} to no yield. Four of the top 10 S_1 lines in GY were derived from LRs selected as superior under drought during the 2004/05 season. The other six S_1 lines were among those selected for superiority under optimal, low N and across the three environments (drought, low N and optimal). Only S_1 line 29 (progeny of LR86) and S_1 line 193 (progeny of LR40) yielded among the top 10 genotypes under drought and optimal conditions. However, only S_1 line 193 was among the top 10 in tolerance to drought conditions (based on SI) and among the top 10 genotypes in GY and optimal conditions. Landraces LR38, LR40, LR84 and LR86 contributed S_1 lines that were among the top 10 under drought conditions (based on selection index) and among the top 10 under optimal (based on GY).

Table 5.3: Ten of the highest and lowest yielding S_1 lines under drought and optimal at Nanga and Chilanga respectively during 2005/06 season

GY and anthesis day (AD) under drought				S_l under drought		GY under optimal		
LR S_1	S_1	GY (t ha^{-1})	AD	S_1	LR	S_1	LR	GY (t ha^{-1})
Top 10								
LR40	187	4.25	105	193	LR40	14	LR38	11.14
LR21	68	4.15	100	68	LR21	32	LR86	8.13
LR84	138	4.04	96	13	LR38	183	LR40	8.12
LR85	150	3.93	95	115	LR74	53	LR76	8.08
LR38	13	3.93	98	38	LR86	29	LR86	7.87
LR40	193	3.88	97	10	LR38	193	LR40	7.86
LR86	29	3.75	99	187	LR40	136	LR84	7.80
LR84	140	3.70	95	140	LR84	5	LR38	7.36
LR12	94	3.63	97	145	LR85	174	LR35	7.24
LR21	61	3.56	99	185	LR40	45	LR76	6.82
Mean		3.88	98					8.04
Bottom 10								
LR93	108	0.18	85	70	LR21	117	LR74	1.08
LR26	15	0.17	109	219	LR49	84	LR11	1.03
LR76	56	0.16	106	112	LR93	203	LR79	1.01
LR21	70	0.08	103	71	LR11	213	LR49	0.91
LR76	43	0.00	113	40	LR86	97	LR12	0.79
LR74	123	0.00	96	15	LR26	138	LR84	0.68
LR86	40	0.00	105	43	LR76	214	LR49	0.68
LR74	114	0.00	105	108	LR93	25	LR26	0.52
LR35	175	0.00	106	44	LR76	43	LR76	0.19
LR26	25	0.00	82	158	LR5	59	LR21	0.16
Mean		0.06	101					0.71
Trial Statistics								
Max		4.25	113					11.14
Min		0.00	80					0.16
Mean		1.76	100					3.69
SE		± 1.09	4.3					± 1.86
LSD		2.15						3.67
P value		0.001	0.00					0.001

The most tolerant genotype to drought was S_1 line 193 (progeny of LR40) which also ranked 6th in GY (Table 5.3). Of the top 10 S_1 lines most tolerant to drought, nine were derived from LRs that ranked among the top 10 genotypes in drought tolerance. The other S_1 line 145 was a progeny of LR85 which ranked 64th in drought tolerance during the 2004/05 season. Of the 56 S_1 lines which were progenies of LRs superior in tolerance to drought, 11% were among the lowest 4% of genotypes in tolerance to drought. Other genotypes were among those found superior under optimal, low N and across all the three environments.

5.3.1.3 Grain yield of testcrosses under drought and optimal conditions

Testcrosses were significant for GY across Luangwa and Lusitu sites (Table 5.4). Locations were also significant ($p \leq 0.05$) and site analysis of results was computed. In determining homogeneity of variances between the trial at Luangwa and that at Lusitu, respective mean square error (MSE) at the sites were used. The ratio of MSE_{large} and MSE_{small} between the two sites was 1.13 and was less than 4, the maximum acceptable ratio (Mead et al., 2003). Therefore, a combined analysis was also computed.

Table 5.4: Analysis of Variance of GY for testcrosses under drought

Fixed term	d.f.	ss	ms	Chi pr
Genotype	99	130.87	1.32	0.02*
Location	1	357.12	357.12	<0.001**
Genotype x Location	99	99.31	1	0.472
Rep within location	2	3.43	1.71	0.18

The trial mean (environmental index) was 1.93t ha^{-1} at Luangwa and 0.68t ha^{-1} at Lusitu. Testcross TC36, a progeny of LR12, was the best yielder in GY based on average rank (Table 5.5). It ranked 7th at Luangwa and 5th at Lusitu. Three checks (ZM421, Pop25 and Tester) were among the top 10 genotypes in GY under drought conditions at the two sites. However, the checks ranked 4th, 9th and 10th and some TCs were superior to them in GY. A check (MM603) was among the lowest 10% in GY under drought conditions.

Table 5.5: Performance of the best and worse 10 TCs and checks (c) under drought conditions at Luangwa, Lusitu and across locations.

		Luangwa		Lusitu		Average rank	
LR	TC	GY ($t\ ha^{-1}$)	Rank	GY ($t\ ha^{-1}$)	Rank	Average rank	Rank of Average rank
Top 10							
LR12	TC36	3.18	7	1.14	5	6.00	1
LR84	TC56	2.63	15	1.19	4	9.50	2
LR12	TC35	2.77	12	1.01	12	12.00	3
ZM421 (c)	ZM421 (c)	2.61	17	1.04	10	13.50	4
LR86	TC14	2.60	18	0.99	15	16.50	5
LR86	TC11	3.31	5	0.77	30	17.50	6
LR12	TC38	2.19	37	1.41	1	19.00	7
LR84	TC53	3.31	6	0.75	33	19.50	8
Pop25 (c)	Pop25 (c)	2.70	13	0.82	26	19.50	9
Tester(c)	Tester(c)	2.40	28	1.00	13	20.50	10
Mean		2.77		1.01			
Bottom 10							
LR21	TC31	1.30	80	0.47	81	80.50	91
LR38	TC69	1.60	62	0.30	100	81.00	92
LR76	TC23	1.22	86	0.48	78	82.00	93
LR85	TC64	1.23	83	0.47	82	82.50	94
LR49	TC91	1.44	68	0.30	99	83.50	95
LR84	TC52	1.27	81	0.39	89	85.00	96
LR93	TC39	1.02	91	0.41	87	89.00	97
LR35	TC70	1.01	93	0.44	85	89.00	98
MM603 (c)	MM603 (c)	1.16	87	0.36	92	89.50	99
LR79	TC86	0.98	97	0.37	90	93.50	100
Mean		1.22		0.40			
Statistics							
Max		4.01		1.41			
Min		0.76		0.30			
Mean		1.93		0.68			
SE		0.88		0.35			
LSD		1.75		0.70			
P value		0.02		0.50			

Based on average rank, LR12, LR84 and LR86 contributed seven TCs which were among the top 10 genotypes in GY under drought conditions. Of these LR84 and LR86 were also found among the top 10 LRs under drought, during the 2004/05 season; while LR12 was selected based on across sites performance.

In comparing performance of genotypes under drought and optimal conditions at the same trial site (Table 5.6), the highest yielding genotype under drought conditions was TC25 (a progeny of LR76) which achieved 4.01t ha^{-1} but ranked 12th under optimal conditions with a yield of 6.02t ha^{-1}. However, this genotype had a drought tolerance index (DTI) also known as relative yield reduction of 33% and ranked 21st in DTI. The highest yielding genotype under optimal conditions was TC1 (7.97t ha^{-1}), a progeny of LR38. However, the testcross was 49th in GY under drought and had a DTI of 0.76. Among all the 10 highest yielding genotypes under drought conditions, there was only one check, MMV600, that ranked 9th under the stress. MMV600 ranked 69th under optimal conditions.

Table 5.6: Performance of testcrosses under drought and optimal conditions at Luangwa

		Drought		Optimal		DTI	
TC	LR	GY (t ha^{-1})	Rank	GY (t ha^{-1})	Rank	DTI (%)	Rank
Top 10							
TC25	LR76	4.01	1	6.02	12	33	21
TC26	LR76	3.82	2	3.10	80	-23	6
TC6	LR38	3.57	3	6.69	7	47	38
TC33	LR11	3.34	4	5.12	30	35	24
TC11	LR86	3.31	5	4.33	45	24	11
TC53	LR84	3.31	6	-	97	-	-
TC36	LR12	3.18	7	4.48	41	29	17
TC88	LR79	3.14	8	-	98	-	-
MMV600 (c)	MMV600	3.01	9	3.50	69	14	9
TC57	LR84	2.96	10	1.28	94	131	3
Mean		3.36		4.32			
Bottom							
TC39	LR93	1.02	91	4.10	50	75	82
TC18	LR86	1.02	92	1.88	91	46	36
TC70	LR35	1.01	93	4.09	51	75	85
TC66	LR85	1.00	94	7.04	5	86	95
TC4	LR38	1.00	95	4.56	39	78	89
ZM521 (c)	ZM521	1.00	96	4.11	49	76	86
TC86	LR79	0.98	97	5.19	27	81	91
TC29	LR21	0.95	98	6.56	8	86	94
TC84	LR40	0.87	99	5.57	21	84	93
TC46	LR74	0.76	100	5.98	13	87	96
Mean		0.61		4.91			
Statistics							
Max		4.01		7.97			

		Drought		Optimal		DTI	
TC	LR	GY (t ha^{-1})	Rank	GY (t ha^{-1})	Rank	DTI (%)	Rank
Min		0.76		0.20			
Mean		1.93		4.29			
SE		0.88		1.97			
LSD		1.75		3.92			
P value		0.02		0.08			

5.3.1.4 Tolerance to drought by testcrosses

A combined analysis showed that TC21 (progeny of LR86) was most tolerant to drought at the two sites. However, individual site analysis showed that it ranked 4th at Lusitu and 29th at Luangwa (Table 5.7). TC45 (progeny of LR74) was most tolerant to drought at Lusitu but ranked 38th at Luangwa and 9th across sites, in tolerating the stress. The most tolerant genotype at Luangwa was TC25 (progeny of LR76) ranked 67th at Lusitu and 13th across sites.

Using selection index, TC25 (progeny of LR76) ranked 1st and 13th under drought and optimal conditions respectively, in trials both conducted at Luangwa (Table 5.7). The other nine most drought tolerant genotypes ranked above 20 under optimal conditions. Similarly, genotypes that ranked high in SI under optimal conditions did not exhibit such superiority under drought conditions. For example, the highest ranking genotype under optimal conditions was TC62 (progeny of LR85), ranked 70th under drought conditions.

Three genotypes that were among the 10% most tolerant to drought at Luangwa were among the least in drought tolerance at Lusitu. However, none of the best 10% in drought tolerance at Lusitu were among the 10% least tolerant to drought at Luangwa.

Table 5.7: Tolerance to drought among testcrosses and checks (c) based on a selection index (SI) under drought and ranking based on GY under optimal conditions

			Ranking based on SI under drought			Rank of TC based on selection index under drought and optimal conditions at Luangwa		
TC	LR	AD Across sites	Across sites	Luangwa	Lusitu	TC	Drought	Optimal
Top 10								
TC21	LR86	61	1	29	4	TC25	1	13
TC11	LR86	62	2	10	24	TC 26	2	52
96 (c)	Tester	62	3	18	7	TC 16	3	26
TC35	LR12	63	4	20	8	TC 83	4	34
TC88	LR79	62	5	27	58	TC 68	5	21
TC33	LR11	62	6	7	34	TC 81	6	60
TC16	LR86	63	7	3	26	TC 33	7	40
TC6	LR38	64	8	95	56	TC 79	8	88
TC45	LR74	58	9	38	1	TC 78	9	78
TC81	LR40	62	10	6	52	TC 11	10	43
Bottom 10								
87 (c)	Pool16	54	91	86	47	TC 39	91	76
TC31	LR21	68	92	76	59	TC 18	92	90
TC52	LR84	62	93	83	75	TC 2	93	56
TC18	LR86	59	94	92	9	TC 4	94	39
TC42	LR93	59	95	87	95	TC 6	95	3
TC49	LR84	65	96	63	74	TC 22	96	80
100 (c)	MMV400	58	97	80	43	TC 57	97	73
TC70	LR35	64	98	77	100	TC 73	98	6
TC86	LR79	65	99	88	87	TC 82	99	89
TC39	LR93	61	100	91	97	TC 84	100	15

5.3.2 Heritability of traits

A combined analysis of results at Luangwa and Lusitu showed that the broad sense heritability (H^2) estimate for GY was 0.17. Individual site analysis showed that H^2 was 0.23 at Luangwa and 0.04 at Lusitu (Table 5.8). The combined analysis also found that H^2 of Tsize to be 0.53 and was highest among the traits considered under drought conditions. Comparing the heritability estimates of traits under drought (Luangwa) and optimal conditions (Luangwa), H^2 of ASI, Tsize, Lsene and Lroll were higher under drought than under well watered conditions. Heritability estimate under drought conditions at Luangwa were 0.68 (ASI), 0.62 (Lroll), 0.27 Lsene and 0.54 (Tsize).

Table 5.8: Heritability estimates of GY and some secondary traits under drought and optimal conditions at Lusitu and Luangwa during the 2006/07 season.

	Drought			Optimal
Trait	Combined	Lusitu	Luangwa	Luangwa
GY	0.17 ± 0.10	0.04 ± 0.99	0.23 ±0.93	0.45 ±0.84
ASI	0.16± 0.96	0.07 ± 0.98	0.68 ± 0.70	0.28 ± 0.91
Tsize	0.53 ± 0.80	0.39 ± 0.87	0.54 ± 0.80	0.32 ± 0.90
Lsene	0.12 ± 0.97	-0.12 ± 1.03	0.27 ± 0.92	0.12 ± 0.97
EPP	0.15 ± 0.96	0.43 ± 0.85	-0.18 ± 1.04	0.26 ± 0.92
Lroll	0.21 ± 0.94	0.15 ± 0.96	0.62 ± 0.74	0.54 ± 0.79
Gtext	-0.40 ± 1.08	0.01 ± 1.00	0.15 ± 0.96	0.26 ± 0.96

Standard error was calculated as square root of MSE/V_p where; MSE = Mean square error and V_p is phenotypic variance of a trait

5.3.3 Trait correlation with grain yield

Across sites, phenotypic correlations (r) of GY with EPP, Lroll, Lsene, Tsize, and Gtext under drought were significant ($p \leq 0.05$), while that with ASI was not (Table 5.9). Anthesis-silking interval had a non-significant positive correlation ($r = 0.020$) with GY under drought conditions.

Table 5.9: Phenotypic correlation of GY with some selected traits under drought and optimal conditions at Lusitu and Luangwa during the 2006/07 season.

Trial site	ASI	EPP	Gtext	Lroll	Lsene	Tsize
Drought across sites	0.020	0.231*	-0.159*	-0.566*	0.307*	-0.170*
Drought at Lusitu	0.254*	0.298*	-0.151	-0.235*	0.202*	0.304*
Drought at Luangwa	-0.316*	0.120	-0.181*	-0.123	0.231*	-0.012
Optimal at Luangwa	-0.164*	0.021	0.321*	-0.066	0.314*	0.201*

*Significant at $p \leq 0.05$

The correlation of GY with Tsize was negative and insignificant (r = -0.012) under drought conditions at Luangwa, but positive and significant (r = 0.201*) under optimal conditions. The correlations between GY and Tsize, and GY and ASI under drought conditions at Lusitu were positive and significant ($p \leq 0.05$). Lsene consistently showed a significant positive correlation with GY. Considering the magnitude of significant correlations under drought, EPP vs. GY was greatest at Lusitu (r = 0.298*), while ASI vs. GY was highest at Luangwa (r = -0.316*).

5.3.3 Use of the selection index to identify drought tolerant genotypes.

Inconsistent trait correlation with GY and a discrepancy in identifying high yielding genotypes under drought, using the selection index (SI), was observed. This led to the re-examination of weights for traits used in calculating SI under drought conditions. Values of trait phenotypic correlations were used as weights while that of GY was $1+\{\Sigma(1-T_i)\}$ where T_i denoted values of trait phenotypic correlation with GY and calculated the new selection index (SI_{new}) for genotypes. Of the 10 highest yielding genotypes when evaluating landraces, SI_{new} identified nine as drought tolerant, while SI identified only five. Similarly of the 10 highest yielding genotypes when evaluating S_1 lines, SI_{new} identified seven as drought tolerant, while SI identified only five. Table 5.10 compares the two indices in identifying high yielding genotypes evaluated at Luangwa and Lusitu under drought conditions.

Table 5.10: Comparison of SI and SI_{new} in identifying drought tolerant genotypes at Luangwa and Lusitu during the 2006/07 season.

SI of highest yielding genotype Luangwa					SI of highest yielding genotype at Lusitu				
TC/c	LR/c	Rank GY	Rank SI	Rank SI_{new}	TC/c	LR	Rank GY	Rank SI	Rank SI_{new}
TC25	LR76	1	1	1	TC38	LR12	1	13	1
TC26	LR76	2	2	2	TC45	LR74	2	1	2
TC6	LR38	3	95	95	TC27	LR76	3	5	3
TC33	LR11	4	7	3	TC56	LR84	4	10	5
TC11	LR86	5	10	4	TC36	LR12	5	15	4
TC53	LR84	6	21	5	TC18	LR86	6	9	8
TC36	LR12	7	12	7	TC73	LR35	7	3	6
TC88	LR79	8	27	6	TC4	LR38	8	6	7
82 (c)	MMV600	9	99	99	TC55	LR84	9	2	9
TC57	LR84	10	97	97	97 (c)	ZM421	10	18	12

The results show that of the 10 highest yielding genotypes at Luangwa, seven were drought tolerant (SI_{new}), while SI found five. Of the 10 most drought tolerant genotypes at Lusitu SI_{new} identified nine of them as drought tolerant, while SI identified seven.

Based on SI_{new}, LR79, LR12, LR76, LR84, LR86, LR38, LR35, LR86 and LR11 were the most tolerant genotypes to drought (Table 12b). Of these, five were among the top 10 in GY under drought conditions. Selecting superior genotypes using SI only identified two landraces, LR86 and LR12, among the 10 highest yielding genotypes under drought conditions. However, use of both selection indices failed to identify TC95, MMV600 and TC57 which were among the top 10 genotypes in GY.

Table 5.11: Comparison of SI in identifying drought tolerant genotypes across sites

Drought tolerant genotypes based on SI_{new}					Drought tolerant genotypes based on SI				
Rank SI_{new}	TC/c	LR/c	Rank of Average of GY	Rank SI	Rank SI	TC	LR	Rank of Average of GY	Rank SI_{new}
1	TC88	LR79	17	5	1	TC21	LR86	71	46
2	TC35	LR12	3	4	2	TC11	LR 86	6	6
3	TC26	LR76	14	14	3	TC96	Tester	10	11
4	76 (c)	Pop25	9	11	4	TC35	LR 12	3	2
5	TC53	LR84	8	21	5	TC88	LR 79	17	1
6	TC11	LR86	6	2	6	TC33	LR 11	29	10
7	TC6	LR38	11	8	7	TC16	LR 86	33	61
8	TC73	LR35	27	12	8	TC6	LR 38	11	7
9	TC14	LR86	5	15	9	TC45	LR 74	35	24
10	TC33	LR11	29	6	10	TC81	LR 40	66	36

5.3.4 General Combining Ability (GCA) effects

GCA effects were estimated as deviations from the grand mean which were divided by the standard deviation among the means. The checks were left out of the calculations of the mean, since they were not crossed to the common tester.
Values greater than two (t-test) were significant ($p \leq 0.05$).

All the highest yielding TCs had significant ($p \leq 0.05$) GCA effects for GY while the 10 lowest yielding TC did not (Table 5.12) under drought conditions across sites. These TCs also had non-significant GCA effects for ASI and Tsize. Less five of the TCs had significant GCA effects for Lsene, EPP, Gtext and Lroll among the highest and lowest yielding genotypes.

Table 5.12: General combing ability estimates for GY and secondary traits of TCs under drought conditions at Luangwa and Lusitu during the 2006/07 season.

TC/c		Estimates of GCA values (number of standard deviations)						
Top 10	GY (t ha^{-1})	GY	ASI	Tsize	Lsene	EPP	Gtext	Lroll
TC88	2.19	2.87*	0.27	-0.45	0.86*	-0.85	-1.20	0.56*
TC35	1.99	2.23*	0.02	1.29	-1.02	0.23	1.37*	-1.56
TC26	1.94	2.06*	-0.47	0.91	-0.11	-0.50	0.34*	-0.17
TC36	1.92	2.02*	0.05	0.14	1.17*	0.28	-1.00	-0.45
TC11	1.89	1.90*	-0.47	-0.41	-1.01	-0.33	0.11	-0.54
TC6	1.88	1.88*	-1.94	1.25	0.48*	0.50*	-0.20	0.39*
TC53	1.84	1.75*	1.18	-0.22	0.40*	-0.19	-1.10	-0.20
TC56	1.84	1.75*	0.17	-0.46	-0.31	-0.15	1.51*	0.06
TC14	1.74	1.44*	-0.04	0.25	-1.04	-0.15	-0.60	0.06
TC33	1.69	1.26*	-1.59	-0.10	-0.13	-0.07	0.57*	-0.04

Table 5.12: General combing ability estimates for GY and secondary traits of TCs under drought conditions at Luangwa and Lusitu during the 2006/07 season, contd.

TC/c		Estimates of GCA values (number of standard deviations)						
Bottom 10	GY (t ha^{-1})	GY	ASI	Tsize	Lsene	EPP	Gtext	Lroll
TC35	0.93	-1.19	2.72	0.65	1.03*	-1.26	-0.75	-0.33
TC66	0.92	-1.19	0.42	-0.04	-1.00	1.42*	-0.18	5.03*
TC23	0.90	-1.25	-0.10	0.57	-0.61	-0.46	-3.98	0.58*
TC70	0.89	-1.29	1.77	-1.45	1.07*	-1.67	0.79*	0.22
TC68	0.87	-1.36	-1.62	-1.66	-2.05	0.11	0.07	-0.04
TC29	0.85	-1.43	0.26	0.58	-2.14	-0.78	0.27	-0.55
TC64	0.78	-1.65	1.46	-1.16	-0.50	-0.68	-0.25	0.15
TC86	0.72	-1.86	1.61	-0.54	0.74*	-0.53	0.42*	-0.58
TC31	0.70	-1.90	-0.16	0.69	-0.06	-0.17	0.12	-0.80
TC91	0.68	-1.97	-0.82	2.34	-2.69	-0.42	-0.2	0.26

*GCA effects significantly different to zero

5.3.5 Genetic Correlation

To determine the effectiveness of selecting high yielding genotypes under optimal environmental conditions while targeting the drought environment, a genetic correlation (r_G) of GY under the two environments was calculated and found to be 0.03. The r_G for GY between the drought trials at Lusitu and Luangwa was 0.01. This suggests that these environments are essentially independent of each other in ranking genotypes.

5.4 Discussion

5.4.1 Genotype x environment interaction effects

The analysis of variance showed that LRs, S_1 lines and TCs evaluated in this study were significantly different ($p \leq 0.05$) under drought conditions (Table 5.2). This meant that the genotypes could be discriminated and superior genotypes under drought selected. However, when evaluating TCs when a combined analysis was possible, genotype x location interaction effects were non-significant ($p \leq 0.05$). Fox et el. (1997) reported that, in the absence of interaction effects, discussion should be focussed on the main effects. The results suggested that a superior genotype could be recommended for cultivation across the drought-affected environments.

5.4.2 Performance of landraces

The results showed wide variation in performance of landraces under drought, with GY ranging from zero (LR28) to 3.97t ha^{-1} (LR74). The highest yielder of all genotypes including checks was a landrace (LR76), and eight of the top nine genotypes for GY were all landraces revealing their potential under drought. Azar et al. (1997) also reported variation in maize landraces in quantitative traits including GY, grain colour and grain texture. Variation enabled selection of genotypes that exhibited preferred characteristics. Mieg et al. (2001) assessed variation for stover digestibility among European landraces. They studied the content of digestible organic matter in stover and found wide variation among the landraces, revealing the potential of the European landraces for forage maize breeding purposes. Results of the current study indicated that LRs had alleles for drought tolerance that enabled them to yield well under the stress. Observed variation in GY and other traits reflected the potential of LRs for use in breeding for drought tolerance.

The 10 lowest yielding genotypes under drought were LRs, indicating that not all LRs had alleles for high yield under drought conditions. In fact the results showed that some LRs yielded nothing under drought. These results implied that prior to their use in a breeding programme the LRs should be screened for appropriate traits and superior genotypes should be identified that could be improved for high yielding ability under drought. Azar et al. (1997) observed some heterosis when the lowest yielding LRs were crossed to high yielding ones of different origin and when the LRs were crossed with inbred lines. The low yielding LRs may have accumulated more physiological survival strategies at the expense of reproductive strategies. Low yielding LRs under this study could still be exploited.

Heritability of GY under drought is low (Bolanos and Edmeades, 1996) and selection of superior genotypes under the stress based on GY alone was not very effective. A selection index was preferred as it summarized the worth of a genotype based on secondary traits (Banziger et al., 2000). Genotypes with the highest selection indices (SI) were considered drought tolerant and were selected for further improvement. Landrace 74 was most tolerant of drought while the best check ZM623 ranked second but all the other three checks were not among the best 10 genotypes in drought tolerance. The four most tolerant landraces under drought were identified as LR74, LR93, LR38 and LR21.

The highest yielding genotypes under optimal conditions (based on GY) were LR35, ZM421 (c), LR5, LR26 and LR49 (in that order). Only LR76 and LR86 were among the top 10 in drought tolerance and also among the top 10 genotypes in performance (GY) under optimal conditions revealing ineffectiveness of selecting for drought tolerance under optimal conditions alone. Landraces LR76 and LR26 were also found among the top 10 highest yielding genotypes under both drought and optimal conditions, suggesting that LR76 was probably the best cultivar across the two environments. Genotypes not among the four best under low N, drought or optimal conditions were selected based on performance across the three environments.

5.4.3 Performance of S_1 lines

Performance of S_1 lines showed that 98 of them were higher yielding than the check (ZM521) variety under drought. Seventy four of the S_1 were significantly higher yielding than the check. The top 10 genotypes in tolerance to drought based on selection index were S_1 lines and were superior to the check. S_1line 193 (progeny of LR40) was the most tolerant genotype under the stress and was followed by S_1 lines 68, 13, 115 and 38 progenies of LR21, LR38, LR74 and LR86, respectively. These results show that the S_1 lines and respective LRs possess useful genetic variation for tolerance to drought.

Nine of the top 10 S_1 lines for tolerance to drought were progenies of landraces that were among the top 10 cultivars for drought tolerance. Further, nine of the top 10 S_1 lines in tolerance to drought were also among the 10 highest yielding genotypes under the stress. These results showed that selection index was effective in identifying superior LRs and S_1 lines under the stress. These findings shows that the respective S_1 lines and, by inference, the LRs have alleles imparting drought tolerance and could be used for crop improvement. These results confirm findings by Tarter et al. (2003) that tropical landraces were a good source of germplasm for broadening the genetic base of USA maize production and to improve productivity. Eight of the 10 least tolerant S_1 lines under drought conditions were progenies of landraces that originated from Region II (four S_1 lines) and Region III (four S_1 lines). These findings implied that genotypes that originated from relatively well watered areas lacked ability to tolerate drought stress. However, none of the 10 most tolerant S_1 lines under drought conditions originated from Region I. Six of the S_1 lines originated from Region II while the other four from Region III. Although 42 S_1 lines that originated from Region I (18.75%) were in the evaluation, the absence of any of them among the 10 most tolerant genotypes under drought conditions prevalent in Region I meant that they were inferior. Probably the genotypes lacked traits of adaptive value for GY which was weighed more than the other traits in the selection index used.

5.4.4 Grain yield of testcrosses under optimal and drought conditions

The trial mean was 1.93t ha^{-1} at Luangwa and 0.68t ha^{-1} at Lusitu. The results showed that the genotypes expressed their GY differently at the two sites or that stress was more severe at Lusitu. Testcross 36 (progeny of LR12) was the best TC in GY based on average rank. It ranked 7th at Luangwa and 5th at Lusitu while the combined analysis ranked the genotype 4th. A combined analysis found TC88 of LR79 as the highest yielding genotype across the two sites. However, the genotype ranked 8th at Luangwa, but 49th at Lusitu. Average rank was used to identify superior genotypes in GY under drought across sites.

Three checks, including the tester, were among the top 10 genotypes under drought conditions. The checks ranked 4th, 9th and 10th and were not significantly inferior except for the tester (ranked 10th) which was significantly inferior to TC11 (progeny of LR86) and TC53 (progeny of LR84). Testcrosses TC36 and TC35 (both progenies of LR 12) and TC56 (progeny of LR84) out yielded the best check. Seven TCs (TC36, TC56, TC35, TC14, TC11, TC38 and TC53) yielded higher than the tester thereby expressing heterosis over the tester. The results mean that the respective TCs and, by inference, their S_1 lines and LRs had the genetic potential to produce high yield under drought and can be used as germplasm for crop improvement targeting drought prone areas of Zambia (Regions I and II). Azar et al. (1997) also found heterosis over inbred lines when they crossed LRs to unrelated flint inbred lines revealing the genetic potential of LRs. In the current study, a check hybrid MM603 was among the lowest 10% in GY under drought showing that the hybrid lacked alleles to tolerate drought.

The highest yielding genotype under drought conditions was TC25 (a progeny of LR76) but it ranked 12th under optimal conditions (although not significantly different to the TC that ranked first). Testcross TC1 (progeny of LR38) that yielded highest under optimal conditions (7.97t ha^{-1}) ranked 49th under drought conditions (1.88t ha^{-1}) and was significantly inferior to TC25 and TC26 under the drought stress. This meant that selection based on GY alone under optimal conditions failed to identify high yielding genotypes under drought. While the highest yielding genotype under drought had a DTI of 33%, the highest yielder under optimal condition had a DTI of 76%. Low DTI is indicative of the ability of a genotype to tolerate drought (Rosielle and Hamblin, 1981). The results meant that identification of drought tolerance indirectly under optimal conditions was ineffective.

5.4.5 Tolerance to drought by testcrosses

High yield under drought reflects the ability of a genotype to tolerate the stress. Testcross TC25 (a progeny of LR76) yielded highest under drought and all the top 10 genotypes in GY under the stress were TCs except MMV600 (check) that ranked 9th. The four highest yielding TCs were progenies of LR76 (two TCs), LR38 and LR11. However, heritability for GY under drought was low and selection based on it alone cannot be very effective (Banziger et al., 1997).

Low DTI under drought indicated tolerance to the stress (Rosielle and Hamblin, 1981). The results showed that TC40 (progeny of LR93) was most tolerant to drought and nine of the top 10 genotypes in low DTI were all progenies of LRs except MMV600 that ranked 9th. The four genotypes with lowest DTI were progenies of LR93 and LR84 (three TCs). However, the selection criteria failed to identify high yielding genotypes. For example, the highest yielding genotype under drought at Luangwa (TC25, progeny of LR76) ranked 21st in DTI. The TC reached anthesis after 74 days of planting in relation to the population anthesis of 67±7 days, implying that anthesis could not explain the high ranking in DTI.

Based on SI, nine TCs were among the top 10 genotypes in drought tolerance (Table 5.7). The TCs were progenies of LR86, LR12, LR79, LR11, LR38, LR74 and LR40 (in that order). Of these LR86, LR38, LR74 and LR40 were among the 10% most tolerant landraces under drought during the 2004/05 season. LR86 and LR40 were also superior across environments, while LR11, LR12 and LR79 were among the four genotypes selected for superiority under low N during 2004/05 (the fourth was LR49). The selection indices were consistent in identifying drought tolerant genotypes. However, there was discrepancy in identifying high yielding genotypes under drought using the selection indices. For example, the most drought tolerant landrace was LR74 ranked 12th in GY during 2004/05 season. The most drought tolerant S_1 line TC193 (progeny of LR40) ranked sixth in GY, while the most drought tolerant testcross TC21 (progeny of LR86) was 71st in average rank of grain yield across the two sites, and ranked 55th in GY based on combined analysis.

The observed discrepancy in identifying high yielding genotypes under drought using the selection indices and variation in correlation of secondary traits with GY (section 5.4.7) motivated the re-examination of weights of secondary traits used in calculating the SI. Lin (1978) observed that some traits were difficult to assign weights and in some instances economic importance of traits varied and needed review. Trait phenotypic correlations with GY were used as respective weights, while that of GY was 1+ $\{\Sigma(1-T_i)\}$ where; T_i denoted values of trait phenotypic correlation with GY. This was to take care of genotypic variance of the traits, which may not be taken care of in full when fixed weights are used (Lin, 1978). Using the new selection index (SI_{new}), of the 13 highest yielding genotypes at Luangwa, 10 genotypes with the highest GY under drought were identified while the initial SI only identified four. The trend was similar at Lusitu; and in evaluating LRs and S_1 lines. Based on SI_{new} LR79, LR12, LR76, LR84, LR86, LR38, LR35, LR86 and LR11 were the most tolerant genotypes to drought across the two sites (Table 5.11). Of these, five were among the top 10 in GY under drought. Selecting superior genotypes under drought conditions using SI, only identified two landraces (LR86 and LR12) among the 10 highest yielding genotypes under drought conditions. These results mean that identification of high yielding genotypes under drought was effective using SI_{new}. At 5% selection intensity LR79, LR12, LR76 and LR84 were selected. During 2004/05 season LR84 was among superior genotypes under drought, LR79 and LR12 were superior under low N while LR76 was superior across all the environments. The result shows that tolerance to low N also provides some tolerance to drought, and vice versa.

Rosielle and Hamblin (1981) defined selection for tolerance as selection for low yield depression. Genotypes with low values of yield reduction were considered tolerant to the stress and identification of such genotypes based on low yield reduction was compared to that of using SI and SI_{new}. Of the top 10 genotypes for DTI, two were among the top 10 in GY, while only one was identified as tolerant to drought by either SI or SI_{new}. The primary interest of developing a drought tolerant variety is that it yields well under the stress and does not simply escape the stress. Genotypes tolerated the drought stress by limiting some functions at the expense of kernel development (Ehlers and Goss, 2003). This was in agreement with Monneveux et al. (2006) who found that the primary mechanism underlying drought tolerance was improved partitioning of assimilates to the ear at flowering, at the expense of tassel and stem growth. Ability to yield well under drought exhibits tolerance to the stress. Therefore, a chosen selection criterion must identify genotypes that yield high under drought, and SI_{new} was found effective.

5.4.6. Heritability estimates and General Combining Ability

The estimate of H^2 for GY was found to be only 0.17 under drought conditions across sites, meaning that much of the observed GY was not determined by genetic causes. However, H^2 under optimal conditions, though twice as much, was also low (0.36) suggesting that selection based on yield alone at the trial sites was not effective. Findings that across the drought sites, Tsize had H^2 of 0.53 and was significantly correlated with GY (-0.170*), meant that you can easily alter tassel size but its effect on yield under stress is low. Therefore, tassel size should not be used alone in selecting for drought tolerance. Estimates of H^2 for ASI, Tsize, Lsene and Lroll were higher under drought than optimal conditions suggesting that the four traits were more reliable for selection under drought than GY, EPP and Gtext. High H^2 estimate for ASI under drought concurred with findings by Ribau et al. (1996).

All the 10 highest yielding genotypes under drought conditions had significant positive effects for GY. However, the GCA effects for all the 10 lowest yielding TCs did not have significant GCA effects for GY ($p \leq 0.05$). The significant GCA effects for GY of the 10 highest yielding genotypes under drought conditions implies that the highest yielding genotypes combined well with the tester (additive gene action) but not well enough in the 10 lowest yielding TCs. These results were in agreement with Derera et al. (2007) who reported that additive gene action conditioned GY under drought conditions. It implies that population improvement was appropriate under drought conditions.

5.4.7 Phenotypic and genotypic correlation

Significant phenotypic correlations were found between GY and EPP, Lroll, Lsene, Tsize, and Gtext. This means that Tsize, which was also found with the highest heritability estimate (among the traits under study), was the most effective trait in identifying superior genotypes under drought conditions. Tassel size was also correlated with GY negatively under drought (Luangwa) but positively under optimal conditions (Luangwa). This means that selecting large Tsize under well watered condition and small tassels under drought was effective in identifying superior genotypes in GY. However, significant positive correlation between GY and Tsize was achieved under drought at Lusitu which meant that the genotypes expressed Tsize differently between the two sites and that small Tsize under drought was not always associated with drought tolerant genotypes.

Anthesis-silking interval had non-significant correlation with GY under drought across sites but its correlation with GY was significant under drought at both Luangwa and Lusitu. The correlation was also significant under optimal conditions at Luangwa. The non-significant correlation across sites could have been as a result of differences in stress level at flowering at the two sites which could have affected flowering. The significant ASI vs. GY correlation confirm findings by Chapman and Edmeades (1999) who found signification correlation of GY with ASI under drought conditions across five drought levels. Findings of this study mean that ASI information was useful in identifying high yielding genotypes under drought and optimal conditions. Considering, the magnitude of significant trait correlation with GY under drought, Lroll had the largest followed by Lsene but their heritability estimates were low under the stress and their expression not reliable. Of the traits under review Tsize offered the most effective strategy for identifying high yielding genotypes under drought.

Effectiveness in selecting superior genotypes under optimal environments while targeting the drought environment depends on genetic correlation (r_G) of GY under the two environments. Genetic correlation (r_G) expresses the extent to which two environments reflect the character that is genetically the same (Falconer and Mackay, 1996). It was found that r_G for GY was 0.03. The low correlation means that genotypes found superior in GY under one environment will not necessarily express their superiority under the other environment. Therefore, indirect selection under optimal conditions, while targeting the drought environment, was not an effective option.

At 5% selection intensity LR79, LR12, LR76 and LR84 were selected. During evaluation of landraces during 2004/05 season, LR84 was among superior genotypes under drought, LR79 and LR12 were superior under low N while LR76 was superior across all the environments.

5.4.8 Selection for drought tolerance

The study has found that indirect selection under optimal conditions when targeting drought environment was not effective because the genetic correlation for GY between the two environments was low. Direct selection under drought conditions made slow progress because correlations between GY and secondary traits used in the selection index were generally weak ($r < 0.5$). Selecting under both optimal and managed stressed conditions simultaneously, that is, only advancing families that do well in both environments is the preferred option. Of the top 10 TCs in GY under drought conditions only four were progenies of LRs among the top 10 under drought conditions during 2004/05 season. When selection was made from both drought and optimal conditions, it was found that seven of the 10 highest yielding TCs under drought conditions were progenies of LRs which were among the 10 highest yielding genotypes under drought and optimal conditions during 2004/05 season. This implies breeding progress will be greater when using data from several environments differing in water stress, than when based on performance under one environment.

5.5 Conclusions and implications to breeding

The study determined a) tolerance to drought; b) genotype x environment interaction effects; c) heritability estimates of traits and; d) correlations of traits of maize genotypes under drought. It was been found that the following landraces were tolerant to drought stress; LR74, LR93, LR38, LR21, LR76, LR40, LR86, LR84, LR58 and LR81. The top 10 S_1 lines for drought tolerance included 193, 68, 13, 115, 38, 10, 187, 140, 145 and 185. The following 10 TCs displayed high tolerance to drought stress:

Testcross	**S_1 line**	**Landrace**	**Region sampled from**
TC88	210	LR79	II
TC35	89	LR12	I
TC26	57	LR76	II
TC53	132	LR84	III
TC11	30	LR86	III
TC6	13	LR38	II
TC73	174	LR35	II
TC14	33	LR86	III
TC33	73	LR11	I
TC75	35	LR35	II

These genotypes would be useful in breeding for drought tolerance. Of the 10 most drought tolerant TCs, six were progenies of LRs which originated from Region II, three from Region III and only two from the drought prone Region I. This suggests that landraces in Region I lacked adaptive alleles for high yield under the stress and were perhaps better at survival. Eight of the 10 most tolerant TCs to drought were progenies of the same parents that contributed eight of the top 10 TCs under low N conditions. The landraces included LR11, LR35, LR38, LR76, LR84 and L86. This meant that breeding for drought tolerance also improved tolerance to low N (Banziger et al., 1999).

Heritability for GY under drought was low (0.17) implying that selection based on it alone is relatively ineffective under stress. Genetic correlation of GY under drought to that under optimal condition was also low (0.03) meaning that indirect selection for drought tolerance under optimal conditions will not be effective either. Therefore, direct selection under drought is considered effective and should use of information on GY, ASI, EPP, Lsene, Lroll and Tsize in a SI whose weights reflect their correlations among these traits. The secondary traits generally had significant but weak correlations with GY under drought conditions. Although GE was not significant for GY of TCs, the lack of genetic correlation for GY genotypes at both sites indicated that different genotypes were selected at each site; data from both should be combined during selection to ensure broad adaptation.

The study found that there is adequate genotypic variation among maize LRs for drought tolerance which can be improved by selection. Landraces and S_1 lines superior in drought tolerance have been identified and should be used as base germplasm for crop improvement in Zambia. The developed superior S_1 lines under drought should be used to develop synthetics or hybrids targeting the drought prone environments in Zambia.

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Chapter 6: Overview of the Thesis

6.1 Introduction

In concluding the thesis, this chapter reviews major findings of the research and discusses its implications to breeding. The following research hypotheses were tested:

i. There is low adoption of improved maize varieties in Zambia because the technologies failed to meet farmer expectations.
ii. Commonly grown maize cultivars are stable in performance across different fertility levels and environments in Zambia.
iii. There is adequate genetic variation among local unimproved maize cultivars (landraces) for tolerance to low nitrogen (N) which could be improved by selection
iv. There is adequate genetic variation among local maize landraces for tolerance to drought which could be improved by selection.

6.2 Major findings and implications to breeding research

6.2.1 Farmer preferences and adoption of maize varieties

The study found that farmers cultivated maize under low input, and 72% achieved less than 1t ha^{-1} irrespective of whether they planted landraces or improved seeds. This means that the farmers did not experience the advantage of planting improved seeds as opposed to landraces. The results implied that the low uptake of improved seeds among small-scale farmers was due to their poor performance under farmer conditions.

The improved varieties probably exhibited dynamic (agronomic) stability, implying that the environment influenced grain yield (GY) of a genotype (Tollenaar and Lee, 2002). Such varieties required application of specified inputs when cultivated under a specific environment in order to adequately exploit their GY potential. Therefore, the improved varieties are inappropriate for farmers unable to afford high levels of inputs. The challenge for plant breeders in Zambia is to develop genotypes that yield well under the farmer crop environment of low inputs. Developing cultivars that exhibit homeostatic stability; i.e. maintain grain yield (GY) across environments, is a preferred option for resource poor small-scale farmers (Fox et al., 1997).

- About 76% of the farmers in the study areas depended on local maize landraces for seed, most of which was farm saved seed, but 22% of the farmers purchased it from within their communities.

  The ultimate goal for a breeder is that the developed variety reaches farmers. A breeder needs to understand the farmer crop production environment before deciding on a breeding objective. This study found that farmers felt that most of the improved varieties did not address their concerns. These results imply that participatory breeding could strengthen a breeding program in addressing farmer concerns. The finding that 22% of farmers purchased landraces implied that the farmers believed that landraces addressed some of their concerns. It also meant that a seed market does exist among the small-scale farmers for an appropriate variety that addresses their important concerns.

- Factors that had a significant ($p \leq 0.05$) influence in causing farmers to adopt improved maize cultivars were food security, the need to apply fertiliser and drought tolerance (in that order). However, drought was not a constraining factor to production in Region III.

  To enhance maize production, cultivars that yield well under low soil fertility (targeting all the Regions) and drought (targeting Regions I and II) conditions should be developed. This requires ability of the genotypes to tolerate the effects of the abiotic stresses and yield well. In developing cultivars that tolerate low soil fertility and drought, use of appropriate germplasm with alleles for performance under these abiotic stresses is important.

- The study found that although farmers perceived the landraces to be low yielding, they believed that they are superior to improved cultivars for: resistance to pests and diseases (65.8%); tolerance to drought (30.8%); tolerance to low soil fertility (40.8%); grain palatability (82.5%); grain storability (91.7); and poundability (88.3%).

In developing drought and low soil fertility tolerant cultivars, inclusion of local landraces with adaptation to these conditions as germplasm is advised. Additional characteristics should include farmer preferred traits such as flintiness, grain and cob sizes, poundability, palatability and storability.

6.2.2 Performance of widely grown cultivars under contrasting fertilisation

- The study found that all nine popular cultivars responded positively to fertilisation applied. The cultivars increased GY as fertilisation (particularly N) increased implying that they exhibited dynamic stability to environments. The cultivars apparently cannot achieve high yields under low fertilization and were therefore inappropriate for farmers who failed to apply fertilizers.

- The nine popular cultivars had significant ($p \leq 0.05$) genotype x fertilisation interaction effects for GY at CHI-1, MASA-1 and CHI-2 ($p \leq 0.10$), and not at LUA-1, LUA-2 and MASA-2. The results meant that the environment differently influenced cultivars at CHI-1, CHI-2 and MASA-1. Absence of genotype x environment interaction effects at LUA-1, LUA-2 and MASA-2 meant that the genotypes were ranked for GY similarly at all fertiliser levels.

  Further, it was found that the cultivars with significant genotype x fertiliser interaction effects did not exhibit crossover type of interaction effects. Therefore, the best cultivars at CHI-1, CHI-2 and MASA-1 were superior only in those specific environments.

  Mean GY showed that the advantage of applying fertiliser was 99%, 24%, and 41% when fully recommended fertilisation, basal dressing only and top dressing only were applied. Improved tolerance to low soil fertility will not only motivate farmers in planting improved seeds but will also increase their GY. Applying fertilizer would almost double GY, irrespective of type of cultivar, if they used the recommended fertilisation; and they would also increase GY by about half, if only top dressing fertiliser was applied. These findings meant that increasing farmer access to fertiliser in Zambia, for example, through subsidies, better infrastructure and dealership network will increase maize production. The results also meant that where resources were limited, application of top dressing nitrogen fertiliser was more effective than basal dressing fertiliser. However, the need to increase access to fertiliser by farmers is well known by the government that supports about 125000 small-scale farmers (12.5% of the farmers) with fertilisers. Financial constraints have limited the further broadening of the intervention (MACO, 2005). However, provision of varieties that tolerate the abiotic stresses, such as low N and drought, is an effective and sustainable partial solution.

- Based on average rank of GY across ENVs and fertilizer treatments, all three landraces yielded higher than all three OPVs. Only hybrid MRI724 outyielded all the landraces. Gankata was ranked the second highest yielding genotype and was followed by MM603, Kazungula, Pandawe, ZM521, MMV600 and MMV400.

  Superiority of LRs challenges plant breeders to develop varieties using a different strategy. Use of LRs as base germplasm will probably accelerate stress tolerance, as they could contribute adaptive traits for such environments having been traditionally managed under low soil fertility. The finding also calls on the seed certification Authority, Seed Control and Certification Institute (SCCI), to evaluate candidate varieties for performance under low inputs as well, to simulate the farmer environment. Popular landraces should also be included in such trials, as checks for performance and release decisions should be based on superiority over the best check.

6.2.3 Genetic variation in local landraces for tolerance to low N and drought

- The study identified testcrosses superior to improved checks under low N, drought and optimal conditions. Thus, landraces and S_1 lines superior under the three environments have also been identified. The study showed that landraces (LRs) had genetic variation for tolerance to low N and drought. Testcrosses that ranked among the top 10 genotypes (10%) under low N, drought and optimal conditions were progenies of LR11, LR12, LR35, LR38, LR40, LR76, LR79, LR84, LR85, LR86 and L93. Also among this group were three checks MM603 (low N), Pop25 (drought) and Tester (optimal).

- Some landraces were superior under more than one environment implying that selecting for genotypes targeting one environment, also selected for performance in the other. Landraces LR11, LR35 and LR76 were ranked among the top 10 genotypes under both Low N and drought. These genotypes should be used for crop improvement, targeting resource poor farmers in drought prone areas of Regions I and II. A variety that exhibits such characteristics will attract many farmer users in such remote areas thereby increasing their GY.

- Landrace LR12 was superior under optimal and drought conditions, suggesting that, it should be used to develop drought tolerant varieties targeting Region II, where drought occasionally occurs. However, such a variety should target farmers with access to fertilisers. This means that the varieties should be developed with high yield potential to enable farmers to obtain returns on their investment in fertilisation.

- There were no genotypes superior under both optimal and low N, a situation that was prevalent in Region II of the country. However, such genotypes should be identified to enable development of varieties targeting these crop environments. To develop genotypes superior under low N and optimal conditions, the highest yielding genotypes under each of the two environments should be crossed and its progenies should be evaluated under low N and optimal conditions. Heterosis over mid-parent values should be used to identify the desirable genotypes.

- Farmers cultivate maize under different crop environments and stability of a variety in GY across environments is important if it is to be widely adopted. Landraces LR38, LR84 and LR86 were superior under low N, drought and optimal conditions. These LRs should be used as germplasm in developing varieties targeting such broad adaptation.

- Landrace LR79 was only superior under drought, while LR40 and LR93 were only superior under low N conditions. Landraces LR74 and LR85 were both superior under optimal conditions only. These LRs could be used as germplasm targeting the respective environments under which they were superior.

- A hybrid, MM603, and an OPV, Pop25 were among the superior genotypes under low N and drought conditions, respectively, while the tester (CML312/CML395) was superior under optimal conditions. These findings suggest that MM603 should be a preferred variety for cultivation where adequate amounts of rainfall were received but N fertiliser was limiting, such as among resource poor farmers in agro-ecological Region II. However, although MM603 was the best check under low N, it ranked 10th of all the genotypes and nine testcrosses were superior to it in this set of trials. Superiority of the LRs under low N means that farmers who lack fertiliser will prefer planting LRs as opposed to improved varieties. This implied that varieties should be developed that yield higher than LRs under low N. Pop25 ranked 4th under drought and should be promoted for cultivation by farmers in drought prone areas especially in Region I, because the variety matured early (< 120d). This study revealed that although Pop25 was superior under drought, it was largely unknown by farmers in the surveyed drought prone areas. This suggests that promotion of the variety by the Zambia Seed Company, that markets it, was inadequate. The study revealed that the tester was superior under optimal conditions and could be a good variety in Region II if it were released.

- In developing varieties that tolerate low N and drought, the choice of genotypes that contribute useful traits towards this objective is a big challenge. Researchers agree that selection should be carried out under the respective abiotic stress. This was confirmed by the modest genetic correlation ($r_G \leq 0.5$) between GY at low N and optimal environments ($r_G = 0.458$), and the low value of r_G for GY between drought and the optimal conditions ($r_G = 0.03$). These findings strictly suggest that indirect selection under optimal conditions alone, while targeting either low N or drought environments would be ineffective.

  However, direct selection based on GY alone under drought or low N conditions was also rather ineffective because heritability of GY under these abiotic stresses was low (Banziger and Cooper, 2001). Although the broad sense heritability estimate of GY was found to be higher under low N (0.38) than under drought (0.17), it was generally lower under these stresses than in optimal environments, implying that direct selection based on GY alone under either stress would be relatively inefficient.

- The results showed that selection for drought tolerance also improved tolerance of genotypes to low N conditions (and vice versa). It was also found that some superior LRs under drought conditions contributed TCs that were superior under optimal conditions. Therefore, in selecting for drought or low N tolerance, genotypes should be selected under optimal and managed stress conditions, simultaneously. Families that do well under both selection environments should be advanced.

- A low drought tolerance index (DTI) or a low N tolerance index (LNTI) based on the degree of GY reduction under stress, reflected tolerance of a genotype to the stress (Rosielle and Hamblin, 1981). In this study, it was found that this selection criterion was ineffective, as it either selected genotypes of low yield potential under stress or non-stress conditions. For example, the highest yielding genotype under drought TC25 (a progeny of LR76) achieved 4.01t ha^{-1} and ranked 12th under optimal condition (6.02t ha^{-1}), ranked 21st in DTI (relative yield reduction). Therefore, based on DTI the TC25 would not be selected at 10% selection intensity.

- Banziger et al. (2000) suggested the use of some secondary traits whose weight and sign were fixed for calculating a selection index (SI). Use of SI has been found to be generally effective, especially under low N. However, the SI requires improvement for identification of high yielding genotypes under both low N and drought conditions. It has been found that correlation weight and sign depended on genotype, and varied under different environments. For example, weight of a trait correlation with GY under drought and optimal trials both located at Luangwa were different. The sign of GY correlation with tassel (Tsize) and that with anthesis-silking interval (ASI) under drought were negative at Luangwa but positive at Lusitu. Therefore, a new selection index (SI_{new}) is proposed where weight of secondary traits are respective coefficients of phenotypic correlation (r) with GY, while that of GY was 1+ $\{\Sigma(1-T_i)\}$ where T_i denoted values of trait phenotypic correlation with GY. This was found superior in selecting genotypes that also yield well under stress. Grain yield, Tsize, ASI, the number of ears per plant (EPP), leaf senescence (Lsene) and leaf rolling (Lroll) were found to be useful in calculating SI for selecting superior genotypes under drought that occurs at flowering.

Under low N, Tsize had moderate heritability (0.56) and a significant correlation (r=0.21*) with GY. Therefore, information on Tsize, ASI, Lsene, EPP, along with that for GY, will be effective in selecting superior genotypes under low N. However, the recommendation to select for increasing Tsize was at variance with other studies that have found that large tassels reduce GY, either physiologically by competition for photosynthates, or physically by shading leaves (Grogan, 1956; Hunter et al., 1969; Mock and Schuetz, 1974). Moderate heritability and significant correlation of Tsize with GY under low N made it a putatively useful secondary trait under the abiotic stress.

- Most farmers selected seeds based on grain texture (flintiness) while a few based selection on grain and ear size. Grain texture had a significant ($p \leq 0.05$) negative correlation with GY (r = - 0.233*) and a low heritability (0.33) under low N. Similarly, significant negative correlation of flintiness with GY (r = - 0.159*) was found under drought and the heritability was low (zero). Negative correlation implies that farmers who based selection on increasing grain texture have been selecting for low GY. Unintentional negative selection for GY probably explains why some landraces and S_1 lines failed to yield under low N and drought. However, these results also found some flinty landraces that were superior to checks in GY and in tolerance to low N and drought, suggesting that they could have accumulated adaptive alleles under these stresses over generations. Such landraces should be used as germplasm when breeding for tolerance to abiotic stress.

- The highest yielding genotypes under each abiotic stress, low N and drought, exhibited significant positive general combining ability (GCA) effects for GY, suggesting that the genotypes combined well with the single cross tester in terms of GY. The positive GCA effects also reflected that additive gene action was important for GY under the stresses. This probably explained why selecting for tolerance to one abiotic stress also selected for tolerance to the other. These findings implied that population improvement was effective under the abiotic stresses.

6.3 Way forward and Conclusions

Resource poor small-scale farmers in Zambia are constrained in cultivating maize by low soil fertility, especially N, and drought. They will readily adopt varieties that increase their food security and have low cost of production in terms of fertiliser, irrigation and seed. Breeding research, especially by the public sector, should target developing varieties that tolerate low N and drought as a long term and sustainable measure. In the short term, the government should put in place measures that increase farmer access to fertiliser. This will double production if farmers applied the recommended rate of fertilisation or increase it by about half if only top dressing fertiliser was applied.

Candidate varieties for release should be tested under defined farmer environments including that under low N and drought. This should begin with defining the crop environments under which candidate varieties should be tested to enable the release of varieties that are best suited to a specific environment. The evaluation of candidate varieties should include popular landraces such as Gankata which demonstrate superiority over some improved varieties. A new variety should only be released when it is better than the best check for traits important to its adoption. This measure will encourage development of superior varieties to those currently grown and their adoption.

This study identified landraces, S_1 lines and testcrosses which were found superior under optimal conditions, low N, drought and across these three environments. It was further found that some landraces were superior in more than one environment. These genotypes should be used as germplasm in developing varieties that target these respective environments. Two parallel approaches are suggested: a) Superior S_1 lines under each environment should be recombined to develop synthetic open pollinated varieties targeting the respective environment; b) Inbred lines should be generated by advancing S_1 lines through to S_5 after which the inbred lines would be used to develop hybrids targeting the environments

Some results of this study have policy implications. It is envisaged that this work will be made available to policy makers in the Ministry of Agriculture and Co-operatives in Zambia for consideration. The issues include: 1) focusing variety development of maize on tolerance to abiotic stresses such as low N and drought; 2) increasing farmer access of fertiliser to double maize yields in Zambia; 3) variety evaluation under abiotic stress including basing release on superiority over the best check.

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