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Combining ability and testcross performance of low N tolerant intermediate maize inbred lines under low soil nitrogen and optimal environments

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Abstract

Low soil nitrogen (low N) threatens maize production in sub-Saharan Africa (SSA). We examined the mode of gene action conditioning grain yield of intermediate maturing inbreds and evaluated lines in hybrid combinations for high yield, stability and tolerance to low N. Thirty-two sets of inbreds were crossed to three elite testers (87036, 1368 and 9071) to generate 96 F₁ hybrids. The testcrosses plus four hybrid checks were evaluated under low (30 kg/ha) and high (90 kg/ha) N environments at three locations for 2 years in Ghana. Significant general combining ability (GCA) and specific combining ability (SCA) effects were detected for grain yield and most measured traits across test environments, indicating that both additive and non-additive gene action governed the inheritance of the traits. GCA effects were greater than SCA effects, indicating that most traits were controlled predominantly by additive gene action and that inbreds with positive significant GCA effects for grain yield and other traits would contribute favourable alleles to progenies across environments. Hybrid CZL 0001 × 9071 possessed high GY, increased EPP, desirable EHT and PLHT and was the highest yielding under each of two research conditions. Significant genetic correlations were observed between GY and PLHT, EPP, EHT, CA and PA implying that improvement of these traits would lead to significant gains in grain yield under low-N conditions. Hybrids CLWN 247 × 9071, ZM523B-29-2-1-1-B*6 × 9071, TZD II 68 × 1368 and P43SCRq Fs100-1-1-8 × 9071 were high-yielding, stable and low-N tolerant and should be tested on-farm and commercialized.

Introduction

Maize remains one of the most important staple food crops in sub-Saharan Africa (SSA). It is consumed across the continent and covers a significant hectareage of the agricultural land (Okweche *et al.*, 2013). However, maize production in SSA is constrained by several biotic and abiotic stresses prominent among which is low-soil nitrogen (Badu-Apraku *et al.*, 2012). The situation is exacerbated by the effects of climate change. Current climate change-related projections present more grim implications for agriculture in Africa, including maize production (Ribeiro and Rodriguez, 2020). Serious research efforts and adequate resources are required to mitigate the effects of climate change in SSA.

Nitrogen uptake by maize plants is critical to improved growth and also serves as a powerful tool for increased maize yield in SSA (Buerkert *et al.*, 2001). Nitrogen is considered the most important nutrient in maize production in SSA and is recognized as the second most limiting factor for plant growth after water (Sangoi *et al.*, 2008). Reduced availability of productive land for agricultural purposes has restricted farmers to cultivation on the same piece of land without fallowing or crop rotation year after year. Poor weed control also increases the incidence of N stress. Collectively, these constraints have resulted in low N being a major constraint of maize production environments in SSA (Banziger and Lafitte, 1997; Buerkert *et al.*, 2001).

Maize production also occurs under low-N environments (Oikeh and Horst, 2001) by low input farmers who continuously crop maize with limited or no use of N fertilizer. This may be attributed to the high cost of fertilizer relative to grain which makes it uneconomical for farmers to apply fertilizer, non-availability of fertilizer when needed most and reduced N-uptake, especially in drought-prone environments due to quick mineralization of organic matter (Banziger and Lafitte, 1997). One effective strategy available to reduce fertilizer cost is to develop maize genotypes with combined high nitrogen use efficiency and high yield potential. Genotypes with high yield potential under low N are also needed to support the rapidly

growing population and provide incentives to farmers who mostly apply modest amounts of N in their maize fields. Improved maize varieties that tolerate low N will help maize farmers in stress-prone areas to obtain better harvests (Zaidi *et al.*, 2003; CIMMYT, 2007). Efforts to increase maize production in low nitrogen soil conditions may contribute considerably to improving food security and well-being in SSA (Masuka *et al.*, 2012). A major strategy adopted for increasing maize yield under low N input conditions in SSA is breeding for improved grain yield under nutrient deficiency or towards specific adaptation to increase grain yield under low-nitrogen conditions. Consequently, many maize improvement programmes in SSA have placed major emphasis on germplasm improvement for low-N tolerance.

Significant genotype-by-environment interactions ($G \times E$) are common phenomena for plants under stress conditions. Consequently, a variety which performs well in one environment during one growing season or year may not perform well in a different period or site within the same region (Sibiya *et al.*, 2012; Badu-Apraku and Fakorede, 2017; Maffoussan *et al.*, 2018). The result is that genotypes exhibit different levels of phenotypic expression under contrasting environmental conditions resulting in crossover performance (Miti, 2007). Genotype \times environment interaction also occurs as a result of differences in the sensitivities of genotypes to the growing conditions in the target environment (Miti, 2007). When $G \times E$ occurs, it is important to determine whether there are important crossover interactions, i.e. rank changes of the genotypes in different environments, so that outstanding genotypes could be selected in different environments (Yan and Tinker, 2006). When there is no change in the rankings of genotypes over environments, there is a non-crossover type of interaction effects, and genotypes with superior means can be recommended for production in all the environments (Yan and Tinker, 2006). Breeders can also use the information on $G \times E$ to identify appropriate locations for selection to maximize grain yield (Yan and Tinker, 2006).

In maize breeding programmes, analysis of general combining ability (GCA) and specific combining ability (SCA) is essential for identifying outstanding inbred lines with good specific combining ability. The analysis also provides information on the type of gene action controlling quantitative traits, thereby assisting breeders in selecting suitable parental lines (Abrha *et al.*, 2013; Girma *et al.*, 2015). To date, reports on the gene action controlling grain yield and other agronomic traits under low soil N conditions in maize remains inconsistent. For example, several researchers (Rizzi *et al.*, 1993; Lafitte and Edmeades, 1995; Below *et al.*, 1997; Kling *et al.*, 1997) have reported a preponderance of additive gene action over the non-additive in the inheritance of grain yield under low N. Similarly, Badu-Apraku *et al.* (2015) reported that additive genetic effects were more important than the non-additive in controlling grain yield and most agronomic traits under low N conditions. In contrast, other authors (Betrán *et al.*, 2003; Makumbi *et al.*, 2011) reported that non-additive gene action regulated grain yield in low-N environments whereas additive gene action controlled grain yield in high-N environments (Below *et al.*, 1997; Betrán *et al.*, 2003; Makumbi *et al.*, 2011). The differences in the findings could be attributed to variations in germplasm utilized and the severity of the stresses imposed during plant growth and development.

Few studies on combining ability using the International Institute of Tropical Agriculture (IITA) and International Maize and Wheat Improvement Center (CIMMYT) extra-early/early

and late/intermediate maturing inbred lines have been conducted under non-stress conditions, drought and well-watered conditions (Adebayo *et al.*, 2014). Based on the results of these studies, some CIMMYT lines were identified for improving the IITA intermediate germplasm. For instance, Ifie (2013) examined the combining ability of IITA and CIMMYT early-maturing inbred lines under *Striga* and low N conditions. Two lines from IITA, TZEI 175 and TZEI 24, possessing alleles for *Striga* tolerance and resistance were proposed for improvement of *Striga* resistance in tropical maize germplasm while TZEI 32 and ENT 16 identified as tolerant to low soil N were proposed for improvement of tolerance to low N. So far, these are the only studies conducted involving the IITA and CIMMYT early maturing white inbred lines under drought and low-N environments even though several drought and low N tolerant early, extra-early, late and intermediate maturing IITA and CIMMYT inbred lines have been identified in the Drought Tolerant Maize for Africa (DTMA) Project panel of inbred lines. Analysis of inter-trait relationships in contrasting environments is imperative in a maize improvement programme involved in genetic enhancement of grain yield and resistance/tolerance to stresses. This is due to the fact that most economic traits, including grain yield, have low heritability because they are quantitatively inherited. Thus, gains from direct selection for such traits are very little. Available alternative is indirect selection through the use of secondary traits that have high genetic correlations with grain yield, high heritability and are easily measured. Such traits can be identified through analysis of trait associations. The genotype-by-trait (GT) analysis proposed by Yan and Kang (2003) is an efficient statistical tool useful for multiple trait-based assessment of genotypes to identify those that are superior for specific traits which could be used as base genotypes in a breeding programme or released for commercialization while also presenting a graphical display of the genetic correlations among traits (Ober *et al.*, 2005; Badu-Apraku and Akinwale, 2010). It is also helpful in identifying appropriate traits for indirect selection for high grain yield while also providing information for detecting unimportant traits.

The present study was therefore conducted to (i) identify high yielding and stable intermediate maize hybrids under low- and high-N growing environments, (ii) determine the combining abilities and mode of gene action controlling low-N tolerance in a set of intermediate maturing maize inbred lines from IITA and CIMMYT, (iii) examine the performance and stability of the hybrids across low- and high-N environments and (iv) investigate trait associations with a view to identifying traits strongly associated with grain yield under low- and high-N conditions.

Materials and methods

Germplasm and generation of crosses

The genetic materials used in the present study were 32 intermediate maturing white inbred lines and three elite inbred testers (9071, 1368 and 87036) obtained from CIMMYT, the Institute of Agricultural Research for Development (IRAD) and IITA (Table 1). The testers 1368 and 9071 were the parents of a commercial single cross hybrid, Obas Super 1 marketed by several seed companies in Nigeria (Menkir *et al.*, 2003). Tester 87036 was also one of the parents of a commercial hybrid highly patronized in Cameroun (Maffoussan, 2014). All the three testers are recognized efficient testers which have been employed by many researchers. For instance, Agbaje *et al.* (2008) employed testers 1368 and

Table 1. List of inbred lines and testers used in the study

Inbred	Pedigree	Source
CLWN 349	HTBAB9 138-5-1.2TL-1-4-2TL-B-ITL-B_	CIMMYT
CML 494	LP~C~F-7-1-2-Z.2.2-8BB	CIMMYT
CLWN 364	SAHCI-5.1.1-5-3-B	CIMMYT
CLWN 341	LP SEQC3-H1-2-2.2-1-1-.a-B	CIMMYT
CLWN 238		CIMMYT
CLRCW 36		CIMMYT
ZM 523B-29-2-1-1-B*6	ZM 523B-29-2-1-1-B*6	CIMMYT
CLWN 359	SA3C4iIC(16X25)-2-4-3-1-B	CIMMYT
CLWN 247	(CL-FAWW11 × CML494)-B-24-2-2-B-B-1-B-8-B-B	CIMMYT
CML 442	CIMMYT M37W/ZM607#bF37sr-2-3sr-6-2-X-8-2-X-1-BBBB	CIMMYT
CML 444	P43C9-1-1-1-1-BBBB	CIMMYT
CML 198/LPSC	CML198/LPSC3H144-1-2-2-2-2-#-BB-1-4-1-1-4-B*4-B-B-B	CIMMYT
CML 395/CML 444	[(CML395/CML444)-B-4-1-3-1-B/CML395//DTPWC8F31-1-1-2-2]-5-1-2-2-BB-B-B-B	CIMMYT
ZM521B-66-4-1-1	ZM521B-66-4-1-1-BB-B-B-B	CIMMYT
CML 444/CML 395/DTPWC8F31	[CML444/CML395//DTPWC8F31-1-1-2-2-BB]-4-2-2-1-1-BB-B-B-B	CIMMYT
Laposta Seq C7-F71-1-2	La Posta Seq C7-F71-1-2-1-1-B-B-B	CIMMYT
CML 254	TUXSEQ.149-2-BBB*II#1-BB-f	CIMMYT
Laposta Seq C7-F18-3-2-1	La Posta Seq C7-F18-3-2-1-1-B-B-B-B-B	CIMMYT
J-16-1	Zm 523-16-2-1-1-B*4	CIMMYT
P43SRCq Fs100-1-1-8	P43SRCqFs100-1-1-8#1-B-13-B1	CIMMYT
TZM 501XKU1414XTZM501		CIMMYT
TZL Comp 3	TZL Comp 3-C2-S2-34-4-1-B	CIMMYT
CZL 068	[LZ956441/LZ966205]-B-3-4-4-BB	CIMMYT
CZL 0713	[SYN-USAB2/SYN-ELIB2]-12-1-1-1-BBB	CIMMYT
CLWN 240		CIMMYT
CZL 00001	INTA-191-2-1-2-B*6	CIMMYT
TZD II 68	TZE-W POP STR 104 S6 40/160-2/3	IITA
TZD II 134	TZE-W POP STR 107 S6 238/254-2/2-3/3-2/4-2/2	IITA
TZD II 140	TZE-W POP STR 105 S6 53/253-1/2-2/3-3/4-2/3	IITA
TZD II 141	TZE-W POP STR 105 S6 53/253-1/2-2/3-2/4-2/3	IITA
CZL 03007	CML445/ZM621B-2-1-2-3-1-BB	CIMMYT
M131		IRAD
87036*		IRAD
1368*	Across 7721 BC ₂ × TZSR	IITA
9071*	N28 × TZSR	IITA

9071 to study heterotic patterns of early maturing maize inbred lines in *Striga*-free and *Striga*-infested environments. Maffoussan *et al.* (2018) employed testers 87036 and 1368 to study genotype-by-environment interactions and yield stability of maize single cross hybrids developed from tropical inbred lines.

The 32 inbred lines were crossed with the three testers using the line by tester mating design to generate 96 hybrids. Crosses were also made among the testers to generate three hybrids used as checks in addition to a released hybrid 'Etubi' from Ghana. The crosses were generated in the research fields of the

CSIR-Crops Research Institute at Kwadaso, Ghana during the minor growing season of 2012.

Experimental sites and field layout

The study was carried out at three locations: Fumesua, Ejura and Kwadaso, experimental fields of the CSIR-Crops Research Institute. Fumesua is in the semi-deciduous forest zone with an altitude of 286 m above sea level and it is located at Latitude 6° 41'N and Longitude 1°28'W. Its mean annual rainfall is 1500

Table 2. Soil chemical properties of experimental sites

Location	Horizon (cm)	pH (1:1)	Organic C (% C)	Total N (% N)	Ex Ca (Cmolc/kg)	Ex Mg (Cmolc/kg)	Ex K (Cmolc/kg)	Ex Na (Cmolc/kg)	Av P (Mg/kg)	2014 Total N levels (%)
Kwadaso	0–15	7.2	1.1	0.10	7.3	1.6	0.37	0.03	145.7	0.09
	15–30	7.1	0.5	0.03	5.3	0.8	0.31	0.02	124.0	0.04
Ejura	0–15	4.7	0.4	0.03	1.9	1.2	0.04	0.13	17.4	0.04
	15–30	4.5	0.3	0.02	1.7	1.4	0.02	0.12	13.5	0.04
Fumesua	0–15	4.7	1.3	0.12	2.7	0.5	0.28	0.52	27.9	0.13
	15–30	4.7	1.1	0.11	2.8	0.6	0.29	0.41	32.1	0.12
Interpretation (Landon, 1991)	High	>6.5	>10.0	>0.5	>10.0	>4.0	>0.6	>1.0	>50.0	
	Low	<5.8	<4.0	<0.2	<4.0	<0.5	<0.2	<1.0	<15.0	

High values have > attached to the values, meaning the parameters measured are high.
Low values have < attached to the values, meaning the parameters measured are low.

mm with mean minimum and maximum temperatures of 21 and 31°C, respectively. The soil is Asuansi series, a ferric Acrisol. Kwadaso is also located in the forest zone. It has a bimodal rainfall distribution pattern. Its mean annual rainfall is 1450 mm with mean minimum and maximum temperatures of 20 and 29°C, respectively. The major season is from late March to mid-July, while the minor season is from mid-September to mid-November. Kwadaso is situated between Latitude 6°43'N and Longitude 1°36'W. The soil is ferric Acrisol. Ejura is in the forest-savanna transition agro-ecological zone. It is located at Latitude 7°40'N and Longitude 1°39'W, and 221.9 m above sea level. The temperature at Ejura ranges from 31 to 34°C with a relative humidity of 55–65%. The soil type at Ejura is Amantin series under the forest and savanna ochrosols and is moderately well drained, permeable and sandy loam (Adu and Asiamah, 1992; MoFA, 2011).

The study sites were depleted of nitrogen by growing maize at a very high population density without fertilizer application and removing the biomass after each harvest for a period of 2 years. Soil samples were taken each year before planting for all the test environments and N content determined at the soil laboratory of the Soil Research Institute in Kumasi. Furthermore, at harvest, there was total plant removal from the field. The soil properties of the experimental fields at Kwadaso, Ejura and Fumesua in 2013 and 2014 are presented in Table 2. Nutrient status, interpreted in accordance with Landon (1991) method of soil analysis, was found to be generally low at all three locations. Nitrogen levels were also found to be low at all locations since amounts <0.2% were recorded. Hence, the results obtained in the present study are expected to represent the true response of genotypes to the nitrogen applied externally. Available nitrogen is defined as nitrogen in a chemical form that can be readily absorbed by plant roots. However, values for this essential parameter were not obtained during this study. Guinto and Catto (2016) reported a statistically significant relationship between available and total nitrogen and concluded that, when refined, total N data can be used as an estimate of available N in non-pastoral soils with a greater degree of confidence.

The experimental design used in the present study was 10 × 10 lattice with two replications. Single row plots, each 5 m long, spaced 0.75 m apart with 0.5 m between plants in each row were used at all locations. Three seeds of the inbred lines were

planted in each hole and thinned to two plants per hill at 2 weeks after emergence to obtain a population density of 53 333 plants/ha. The experimental fields were divided into low (30 kg N/ha) and high (90 kg N/ha) nitrogen blocks. Nitrogen was applied in the form of sulphate of ammonia. Both low-N and high-N blocks received 60 kg P/ha as single superphosphate (P₂O₅) and 60 kg K/ha as muriate of potash (K₂O). The trials were kept weed-free with the application of pre- and post-emergence herbicides, primextra and paraquat, each at 5 litres/ha and subsequently, by hand weeding.

Data collection

Data recorded included days to 50% silking (DTS) as the number of days from planting to when 50% of the plants had emerged silks, and days to anthesis (DTA) when 50% of the plants had shed pollen. The anthesis-silking interval (ASI) was calculated as the difference between days to 50% silking and 50% anthesis. Plant height (PHT) was measured as the distance from the base of the plant to the height of the first tassel branch while ear height (EHT) was measured as the distance to the node bearing the upper ear, respectively. Plant aspect (PASP) was based on the assessment of the general architecture of plants in a plot as they appeared to the sight and was rated on a scale of 1–5 where, 1 = excellent overall phenotypic appeal, 2 = very good overall phenotypic appeal, 3 = good overall phenotypic appeal, 4 = poor overall phenotypic appeal and 5 = very poor overall phenotypic appeal. The number of ears per plant (EPP) was obtained by dividing the total number of ears per plot by the number of plants harvested. Chlorophyll concentration of the ear leaf of five plants per plot was randomly selected and measured at approximately 2 weeks after anthesis (WAA) with a portable SPAD meter (CCM-200 plus-opti sciences).

For trials conducted under N stress, harvested ears from each plot were shelled to determine the percentage of grain moisture. Grain yield in kg/ha was computed from the shelled grain weight, adjusted to 15% moisture. For the high N plots, a shelling percentage of 80% was assumed for all genotypes and grain yield (obtained from ear weight and converted to kg/ha) was adjusted to 15% moisture.

Statistical analysis

Analysis of variance (ANOVA) was performed on plot means for grain yield and other agronomic characters for each environment and across environments using PROC GLM procedure of SAS software, version 9.3 (SAS Institute, 2008). Each environment was defined as year \times site \times nitrogen treatment. Environmental effects were treated as random and genotypes as fixed effects. The line \times tester analysis (Kempthorne, 1957) was used for crosses excluding the checks for low N environments, high N environments and across environments. *F* tests for line, tester and line \times tester mean squares were computed using the mean squares for their respective interactions with environment. The mean squares attributable to environment \times line \times tester was tested using the pooled error mean squares. The main effects of line and tester represented the general combining ability (GCA) effects while line \times tester interaction represented specific combining ability (SCA) effects. The source of variation for hybrids was partitioned into variability due to lines, testers and line \times testers. Estimates of GCA of a tester (male) were obtained based on its performance in F_1 hybrid combinations with all possible lines (females). Similarly, GCA of a line was determined from its performance in F_1 hybrid combinations with all possible testers. GCA and SCA effects were determined for each agronomic trait under each N environment and across environments. Estimates of GCA and SCA were calculated and their significance determined by *t* tests.

The yield data were further subjected to genotype main effect plus genotype \times environment interaction (GGE) biplot analysis to decompose the $G \times E$ interactions of each experiment using the GGE biplot windows application (Yan *et al.*, 2000; Yan, 2001). The GGE biplot model equation is:

$$Y_{ij} - Y_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \sum ij$$

where Y_{ij} is the average yield of genotype i in environment j , Y_j is the average yield across all genotypes in environment j , λ_1 and λ_2 are the singular values for principal component (PC)1 and PC2, ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores for genotype i , η_{j1} and η_{j2} are the PC1 and PC2 scores for environment j and $\sum ij$ is the residual of the model associated with the genotype i in environment j . The data were not transformed (Transform = 0), not standardized (Scale = 0) and were environment-centred (Centring = 2). The GT analysis was conducted using R (software) package GEA-R (version 4.0) (Pacheco *et al.*, 2016). Prior to GT analysis, the data for the selected 30 hybrids (top 10, middle 10 and worst 10) were standard deviation-standardized (mean = 0, standard deviation = 1) to reduce the confounding effects due to the differences in the scales of measurement of the agronomic traits involved in the analysis. Thus, the outputs are appropriate for visualizing the genotypes and trait relationships. The biplot model equation for the $G \times T$ analysis is as follows:

$$(\hat{Y}_{ij} - \mu - \beta_j)/d_j = \lambda_1 g_{i1} e_{1j} + \lambda_2 g_{i2} e_{2j} + \varepsilon_{ij}$$

where \hat{Y}_{ij} is the genetic value of the combination between inbred i and trait j ; μ is the mean of all combinations involving trait j ; β_j is the main effect of trait j ; λ_1 and λ_2 are the singular values for Principal component (PRC)1 and PRC2; g_{i1} and g_{i2} are the PRC1 and PRC2 eigenvectors, respectively, for inbred i ; e_{1j} and e_{2j} are the PRC1 and PRC2 eigenvectors, respectively, for trait j ;

d_j is the phenotypic standard deviation (with mean zero and standard deviation of 1); and ε_{ij} is the residual of the model associated with the combination of inbred i and trait j .

Results

Analysis of variance and combining ability of grain yield and other traits

Across low N environments, the ANOVA of the single crosses revealed significant ($P < 0.05$) to highly significant ($P < 0.01$) mean squares for genotype (G), environment (E) and genotype \times environment interaction (GEI) for the measured traits except the stay green characteristic for GEI (Table 3). Significant differences were observed among genotypes, environments and GEI for all traits except G for ears per plant and GEI for ears per plant and plant aspect under high N environments (Table 4).

Partitioning of the entries (genotypes) into components revealed that GCA of line (GCA_l) and GCA of tester (GCA_t) and SCA mean squares were significant for all measured traits under low N except for the line GCA for plant aspect, SCA for plant height, ears per plant, stay green characteristic, plant aspect, husk cover and chlorophyll content (Table 3). $GCA_l \times$ environment interactions were significant for all traits except the stay green characteristic, plant aspect, husk cover and chlorophyll content while $GCA_t \times$ environment interactions were significant for all traits except days to silking and anthesis. SCA \times environment interactions were not significant for most traits. The GCA of line and tester variances were larger than those of SCA for all traits under low N environments.

Under high N environments, GCA_l and GCA_t were significant for all traits except ears per plant (Table 4). SCA effects were significant for grain yield, days to silking and anthesis, anthesis silking interval, plant aspect and husk cover. GCA \times environment interaction for line and tester were significant for all traits except ears per plant and chlorophyll content for $GCA_l \times$ environment and ear height and plant height for $GCA_t \times$ environment. Similar to low N environments, SCA by environment interactions were not significant for most measured traits and GCA of line and tester variances were larger than those of SCA for measured traits.

Under low N conditions, GCA effects for grain yield ranged from -400.0 for TZL Comp3 to 240.0 for CML395/CML444 (Table 5). Out of the 32 inbred lines, only CLWN 247, TZD II 68 and ZM523B-29-2-1-1-B*6 showed significant and positive GCA effects for grain yield. Only one of the testers, 9071 showed significant positive GCA effects for grain yield. Negative significant GCA effects for days to silking and anthesis silking interval were observed for the inbred lines CLWN 349, CML 442, Laposta Seq C7-F18-3-2-1, Laposta Seq C7-F71-1-1-2, TZD II68, ZM 521B-66-4-1-1, ZM523B-29-2-1-1-B*. Two testers 1368 and 87036 also showed significant negative GCA effects for days to silking. Inbred lines Laposta Seq C7-F18-3-2-1 and TZD II 68, as well as the tester 9071 displayed significant positive GCA effects for plant height. Significant negative GCA effects for stay green characteristic were observed for inbred lines CML 395/CML 444, CML 442, CZL 068, Laposta Seq C7-F71-1-1-2 and the tester 87036. Only CZL 00001 showed significant negative GCA effects for plant aspect. A positive significant GCA effect for chlorophyll content was observed for CML 198/LPSC, CML 254, CML 442, CZL 0713, Laposta Seq C7-F18-3-2-1, Laposta Seq C7-F71-1-1-2 and the tester 9071. Under high N environments, significant positive GCA effects for grain yield were

Table 3. Line × tester analysis of grain yield and other agronomic traits of 32 intermediate maturing white inbred lines across low N environments

Source of variation	DF	GY (kg/ha)	DTS	DTA	ASI	EHT (cm)	PHT (cm)	EPP	SG (1-9)	PASP	EASP	HC	CC
Envt	5	83797560.7 (<i>P</i> < 0.01)	4181.42 (<i>P</i> < 0.01)	3236.49 (<i>P</i> < 0.01)	146.61** (<i>P</i> < 0.01)	17887.60** (<i>P</i> < 0.01)	80400.10** (<i>P</i> < 0.01)	3.69** (<i>P</i> < 0.01)	39.03** (<i>P</i> < 0.01)	81.52** (<i>P</i> < 0.01)	18.82** (<i>P</i> < 0.01)	65.58** (<i>P</i> < 0.01)	7601.39** (<i>P</i> < 0.01)
Entry	95	1676145.7**	24.14**	19.17**	2.22**	687.27**	942.12**	0.06**	0.94**	0.35*	0.96**	0.29**	97.88**
Envt × Entry	475	853336.5**	5.40**	3.63**	1.64**	155.69**	425.13**	0.06**	0.45 ns	0.32*	0.73**	0.23*	36.67**
Line (GCA)	31	2048032.7**	38.17**	31.46**	3.02**	891.24**	1874.65**	0.08**	1.67**	0.44 ns	1.27**	0.44**	183.55**
Tester (GCA)	2	18190061**	574.93**	427.30**	15.13**	12710.50**	8322.58**	0.24**	16.20**	1.80**	1.76*	0.90*	1402.61**
Envt × Line(GCA)	155	937557.3**	6.95**	4.962**	1.90**	219.26**	609.27**	0.07**	0.57 ns	0.37 ns	1.03**	0.26 ns	42.43 ns
Envt × Tester (GCA)	10	5405532.2 (<i>P</i> < 0.01)	6.82(NS)	3.08 (NS)	4.20 (<i>P</i> < 0.01)	740.99 (<i>P</i> < 0.01)	1192.72 (<i>P</i> < 0.01)	0.18 (<i>P</i> < 0.01)	1.43 (<i>P</i> < 0.01)	0.85 (<i>P</i> < 0.05)	2.05 (<i>P</i> < 0.01)	0.95 (<i>P</i> < 0.01)	100.81 (<i>P</i> < 0.01)
Line × Tester (SCA)	62	1192775.9**	7.72**	5.19*	2.02**	285.92**	546.32 ns	0.06 ns	0.60 ns	0.36 ns	0.89**	0.27 ns	45.39 ns
Envt × Line × Tester(SCA)	310	851950.5**	6.95**	4.68**	1.68**	166.57 ns	460.79 ns	0.06**	0.50 ns	0.34 ns	0.61 ns	0.25 ns	36.36 ns
Error	575	226378	5.25	3.59	1.21	167.03	415.662	0.04	0.57	0.42	0.53	0.23	36.09

GY, grain yield; DTS, days to silk; DTA, days to anthesis; ASI, anthesis silking interval; PHT, plant height; EHT, ear height; EPP, number of ears per plant; SG, stay green; PASP, plant aspect; EASP, ear aspect; HC, husk cover.

*, **Significant at 0.05 and 0.01 probability levels, respectively, and ns: not significant.

Table 4. Line × tester analysis of grain yield and other agronomic traits of 32 intermediate maturing white inbred lines across high N environments

Source of variation	DF	GY (kg/ha)	DTS	DTA	ASI	EHT (cm)	PHT (cm)	EPP	SG (1-9)	PASP	EASP	HC	CC
Envt	5	154917972**	5161.99**	4066.14**	215.47**	21941.92**	77045.40**	21.76**	107.82**	94.15**	15.39**	53.80**	8989.30**
Entry	95	3315746.9**	26.51**	20.44**	1.59**	598.29**	787.41**	0.04 ns	0.61**	0.55**	0.87**	0.56**	192.09**
Envt × Entry	475	1723694.2**	3.86**	2.83**	1.06**	146.79*	262.64*	0.03 ns	0.31**	0.33*	0.54 ns	0.43**	49.19**
Line (GCA)	31	4788592.3**	38.82**	31.92**	1.46**	817.63**	1288.91**	0.04 ns	0.86**	0.66**	1.43**	0.45*	329.84**
Tester (GCA)	2	31287146.8**	669.70**	505.37**	15.71**	11011.63**	8498.81**	0.11 ns	12.15**	4.11**	2.27*	3.22**	2821.78**
Envt × Line (GCA)	155	2072081.4**	5.61**	4.25**	1.18**	284.11**	523.82**	0.04 ns	0.42*	0.45*	0.72*	0.56**	63.34 ns
Envt × Tester (GCA)	10	4894530.4**	19.10**	14.23**	2.09**	161.44 ns	305.1 ns	0.09**	0.71*	1.22**	1.46**	1.61**	177.20**
Line × Tester (SCA)	62	2076478.3**	6.31**	4.34**	1.39**	197.48 ns	469.1 ns	0.04 ns	0.36 ns	0.47*	0.58 ns	0.53**	57.79 ns
Envt × Line × Tester (SCA)	310	1648246.2**	4.62*	3.32*	1.25**	146.94 ns	287.94 ns	0.03 ns	0.29 ns	0.38	0.492	0.43**	43.93 ns
Error	575	820467	3.93	2.83	0.78	152.09	338.48	0.04	0.32	0.35	0.57	0.31	56.29

GY, grain yield; DTS, days to silk; DTA, days to anthesis; ASI, anthesis silking interval; PHT, plant height; EHT, ear height; EPP, number of ears per plant; SG, stay green; PASP, plant aspect; EASP, ear aspect; HC, husk cover.

*, **Significant at 0.05 and 0.01 probability levels, respectively, and ns: not significant.

Table 5. General combining ability effects of lines and testers for grain yield and other agronomic traits under low N environments

Line	GY (kg/ha)	DTS	DTA	ASI	EHT (cm)	PHT (cm)	EPP	SG	PASP	EASP	HC	CC
CLRCW 36	-301.76	2.44**	2.00**	0.44	-0.20	2.03	-0.04	0.11	0.04	0.17	0.11	-2.90*
CLWN 238	-213.50	0.41	1.00**	-0.59*	0.52	-9.21*	-0.03	0.11	0.09	-0.03	0.06	-1.26
CLWN 240	106.49	0.94*	0.64	0.30	5.72*	3.56	-0.02	0.36**	-0.02	0.00	0.03	-3.94**
CLWN 247	425.20**	0.36	0.72	-0.37	7.90**	-0.72	0.07	0.14	0.12	-0.28	0.14	-1.65
CLWN 341	-142.58	1.66	1.39**	0.27	0.62	-0.95	0.01	0.11	0.06	0.03	0.00	-3.13**
CLWN 349	-316.64	-0.09*	0.03	-0.12	-6.90**	3.34	0.01	0.05	0.06	0.19	0.09	0.08
CLWN 359	48.69	-0.26	-0.11	-0.14	-4.86*	1.11	-0.07	-0.14	0.01	-0.03	0.06	0.57
CLWN 364	197.14	0.38	0.25	0.13	-1.98	3.92	-0.02	-0.11	-0.13	-0.17	-0.03	-1.81
CML 444/CML 395/DTPWC8F31	-319.19*	0.66	0.72	-0.06	-3.99	-12.28	-0.05	0.08	0.06	0.33*	0.03	-1.77
CML 198/LPSC	124.29	-0.70	-0.47	-0.23	-4.45	-1.01	0.01	0.17	-0.10	0.11	-0.08	2.83**
CML 254	-262.59	0.66	0.47	0.19	5.10*	5.14	-0.04	0.28	0.06	-0.06	0.09	2.58*
CML 395/CML 444	239.97	-0.70	-0.81*	0.11	-1.14	-4.11	0.05	-0.50**	-0.05	-0.08	-0.14	1.02
CML 442	-57.35	-1.28**	-1.50**	0.22	-4.85*	-6.05	0.01	-0.25*	-0.10	0.22	0.00	5.06**
CML 444	-56.24	1.44**	1.28**	0.16	7.73	1.71	-0.04	0.28*	0.01	-0.11	-0.03	-3.29**
CML 494	46.64	0.11	0.00	0.11	1.19	-6.87	0.03	0.00	-0.13	-0.03	-0.11	-0.43
CZL 00001	42.13	0.24	0.03	0.22	-4.79*	-1.99	0.06	-0.08	-0.27**	-0.31	-0.14	1.94
CZL 03007	-95.51	0.36	0.42	-0.06	-3.05	1.11	0.05	0.30*	0.12	-0.17	0.06	-2.32*
CZL 068	114.28	-0.64	-0.97**	0.33	-9.57**	-9.89*	0.05	-0.39**	-0.10	0.05	-0.08	1.53
CZL 0713	-106.27	-0.62	-0.50	-0.12	5.32*	4.57	-0.03	-0.22	-0.08	-0.17	-0.11	3.06**
Laposta Seq C7-F71-1-1-2	49.22	-1.20**	-1.22**	0.02	-2.35	0.89	0.02	-0.39**	-0.02	0.17	-0.03	3.35**
M131	201.86	-0.34	-0.56	0.22	4.19	5.76	0.09	0.08	-0.02	0.05	0.00	0.76
P43SRCq Fs100-1-1-8	100.20	-0.09	0.33	-0.42	1.53	5.05	0.00	-0.11	-0.16	-0.11	-0.25	0.13
TZL comp 3	-399.98*	1.13	1.28**	-0.14	-7.01**	-19.48**	-0.05	-0.06	0.17	0.22	0.09	-1.96
TZM 501 × KU 1414 × 43 TZM 501	-97.86	0.80	0.55	0.25	-4.24	-9.31*	0.03	0.22	-0.05	-0.08	0.00	0.11
TZD II 134	48.09	-0.01	-0.33	0.33	11.53**	7.89	0.01	0.03	0.09	-0.28	-0.03	1.72
TZD II 140	-90.11	0.16	0.03	0.13	0.06	5.22	-0.07	0.19	0.29**	0.42*	0.34**	0.21
TZD II 141	30.64	0.24	0.36	-0.12	4.82*	0.68	-0.04	0.17	0.09	-0.14	0.14	-2.23*
TZD II 68	580.35**	-1.98**	-2.00**	0.02	-2.98	12.17**	0.08	-0.11	-0.05	-0.14	-0.16*	-1.54
ZM 521B-66-4-1-1	-340.44*	-1.45**	-0.86	-0.59*	-2.93	-8.37*	-0.03	-0.22	0.04	0.33*	-0.03	1.23
ZM523B-29-2-1-1-B*6	434.42**	-1.73**	-1.33**	-0.39	3.95	7.73	0.05	-0.08	0.01	-0.25	0.03	1.67
SE	158.84	0.43	0.37	0.23	2.43	4.05	0.04	0.12	0.10	0.17	0.08	1.07
Tester												
1368	-174.86	-0.23*	-0.09	-0.14	-4.73**	-4.80**	-0.02	0.15**	0.08*	0.05	0.05	0.07
9071	243.758*	1.32**	1.10	0.23	6.41**	4.49**	0.03	0.09	-0.04	-0.07	0.01	-1.95**
87036	-68.90	-1.09**	-1.01	-0.08	-1.68	0.31	0.00	-0.23**	-0.04	0.02	-0.05	1.87**
SE	96.87	0.11	0.07	0.86	1.13	1.44	0.02	0.05	0.04	0.06	0.04	0.42

*, **Significant at 0.05 and 0.01 probability levels, respectively.

observed for lines CLWN 247, CLWN 364, CML 395/CML 444 CZL 00001 and tester 9071 (Table 6). Inbred lines CML 395/CML 444, CML 442, CZL 068, CZL 0713, J-16-1, Laposta Seq C7-F18-3-2-1, Laposta Seq C7-F71-1-1-2, TZD II 140, TZD II 68 and tester 1368 exhibited significant negative GCA effects for days to silking. Inbred lines CML 395/CML 444, CZL 068 and CZL 0713 showed significant negative GCA effects for stay green characteristic. Line CZL 0713 had significant negative GCA effects for both plant and ear aspects, while CLWN 240 and CML 494 had significant negative GCA effects for ear aspect. The two laposta lines, Laposta Seq C7-F18-3-2-1 and Laposta Seq C7-F71-1-1-2 had significant positive GCA effects for chlorophyll content. Both negative and positive estimates of SCA effects (line by tester) for grain yield were observed among crosses across low N and high N environments (Tables 7 and 8, respectively). Significant and positive SCA effects were observed for crosses TZD II 68 × 1368, CZL 0713 × 1368, MI31 × 1368, CLWN 359 × 9071, TZM 501 × KU 1414 × 43 TZM501 × 9071 and TZL comp 3 × 87036 under low N environments, with the highest SCA effects detected for TZD II 68 × 1368. These crosses with the exception of TZL comp 3 × 87036 were among the best 20 hybrids selected across low N environments. Across high N environments, significant positive SCA effects were observed for the crosses CLWN 359 × 1368, CML 494 × 1368, CZL 00001 × 9071, Laposta Seq C7-F18-3-2-1 × 9071, CLWN 349 × 87036 and Laposta Seq C7-F71-1-1-2 × 87036. CZL 00001 × 9071 had the highest SCA effects. These hybrids also produced high yields and were among the best 20 testcrosses except for Laposta Seq C7-F71-1-1-2 × 87036.

The relative importance of GCA and SCA effects was determined as the ratio of GCA effects on the total genetic effects using the sum of squares. The closer the ratio was to unity, the greater was the predictability based on GCA (Baker, 1978). GCA sums of squares (GCA of line plus GCA of tester) varied from 47.5% for ears per plant to 90.0% for days to anthesis. The SCA sum of squares varied from 10.0% for days to anthesis to 52.5% for ears per plant. The SCA sum of squares were larger than GCA sum of squares for ears per plant (52.5%) and husk cover (50.9%) whereas GCA sum of squares were larger for all other traits across environments. Across low N environments, GCA effects varied from 43.7% for plant aspect to 85.0% for days to anthesis. The GCA effects accounted for 57.5% of the total genetic effects for grain yield while the contribution from SCA was 31.4%. The SCA effects varied from 15.0% for days to anthesis to 56.3% for plant aspect. The SCA sum of squares were larger than GCA sum of squares for ears per plant (53.6%), anthesis silking interval (50.3%), plant aspect (56.3%), ear aspect (56.2) and husk cover (52.1%) whereas GCA sum of squares were larger for the other traits. Across high N environments, the contribution of GCA to genotypic sum of squares ranged from 35.3% for ears per plant to 88.2% for days to anthesis, while the SCA effects varied from 11.9% for days to anthesis to 64.7% for ears per plant. The GCA effects accounted for 62.1% of the total genetic effects for grain yield. Similarly, across low N environments, SCA sum of squares were larger than GCA sum of squares for ears per plant (64.7%), anthesis silking interval (52.9%), plant aspect (50.5%) and husk cover (61.5%) whereas GCA sums of squares were larger for the other measured traits.

Across low N, grain yield ranged from 528 kg/ha for TZL Comp3 × 1368 to 2718 kg/ha for TZD II68 × 1368 with a mean of 1784 kg/ha (Table 9). Grain yield across high N conditions ranged from 2340 kg/ha for ZM521B-66-4-1 × 1368 to 5348 kg/ha for

CZL 00001 × 9071 with a mean of 3713 kg/ha (Table 10). The best check across research environments was 87036 × 9071 which had grain yield of 1876, 3558 and 2717 kg/ha under low, high and across N environments, respectively. The high yield of TZD II68 × 1368 was associated with increased plant height, ears per plant, reduced ASI and good plant aspect. The highest yielding hybrid across low and high N out yielded the best check by more than 10%.

Performance and stability hybrids across environments

The GGE biplot analysis of grain yield of the best 20 and worst five hybrids and the four checks across 12 environments revealed that the principal component axis 1 (PC1) explained 43.1% of total variation while PC2 explained 17.2% of the total variation in grain yield across the environments with both axes explaining 60.3% of the total variation in grain yield. In Fig. 1, the entry/ tester GGE biplot revealed CZL 00001 × 9071 (1), Laposta Seq C7-F18-3-2-1 × 9071 (2), CLWN 247 × 9071 (3), CLWN 364 × 9071 (4) and TZD II 68 × 1368 (5) as the five top yielding hybrids. The lowest yielding hybrids were TZL Comp3 × 1368 (25), ZM 521 B-66-4-1-1 × 1368 (24), CML 254 × 1368 (23) and CLWN 238 × 1368 (22). The hybrids CZL 00001 × 9071 (1) and CLWN 247 × 9071 (3) were high yielding but highly unstable while CML 395/CML 444 × 9071 (6), TZD II 134 × 9071 (8), CML 494 × 1368 (12), CML 494 × 9071 (19) and CLWN 349 × 1368 (21) were the most stable hybrids. Among the hybrids that were most stable, CML 395/CML 444 × 9071 (6) and CML 494 × 1368 (12) were among the best 20 under high N, while CML 395/CML 444 × 9071 (6) was among the best 20 under low N. Across environments, hybrids CML 494 × 1368 (12), CML 494 × 9071 (19) and CML 395/CML 444 × 9071 (6) were among the best 20. Hybrids CML 494 × 1368(12), TZD II 134 × 9071 (8), CML 395/CML 444 × 9071(6) and TZDII 68 × 1368 (5) were the best hybrids in terms of stability and yield performance across test environments.

The vertex cultivar in each sector of the polygon view represented the highest yielding cultivar in the location that fell within that particular sector (Fig. 2). Hybrids 7, 15 and 3 were the highest yielding at KWH14 and KWH13 (high N environments at Kwadaso in 2013 and 2014), while hybrid 1 exhibited the highest performance at FUMH14, FUMH14 and EJH14. The vertex hybrids 9, 25 and 24 were the lowest yielding at all or some locations. Furthermore, no environment fell into the sectors with 29, 27, 26, 21, 23, 22, 28, 20, 17, 13 and 18, indicating that these hybrids were not the best in any of those environments. Hybrids within the polygon, particularly those located close to the biplot origin were less responsive compared to the vertex hybrids.

The representativeness and discriminating ability of the environments is presented in Fig. 3. The straight line from the origin to the coordinates where an environment falls was called the research environment vector while the straight line with a single arrow which passed through the origin and the average environment represented the average environment axis (AEA). The vector length measured its discriminating power to assess cultivars under the test environments, that is, the longer the vector length the more discriminating was the environment. The angle between an environment and AEA measured its representativeness; therefore, the shorter the projection was from the marker of an environment, the more representative was the environment. According to Yan *et al.* (2010), the shorter environmental vectors indicated that the specific environments were not strongly correlated with

Table 6. General combining ability effects of lines and testers for grain yield and other agronomic traits under high N environments

Line	GY (kg/ha)	DTS	DTA	ASI	EHT (cm)	PHT (cm)	EPP	SG	PASP	EASP	CC
CLRCW 36	-3.18	1.94**	1.60**	0.34	2.80	7.89*	-0.01	0.07	0.04	-0.13	-6.21**
CLWN 238	2.91	1.47**	1.05**	0.42*	3.63	-6.93	0.02	0.13	-0.02	-0.05	-5.64**
CLWN 240	110.06	0.72	0.71*	0.01	4.20	1.78	-0.03	-0.04	-0.07	-0.30*	-3.31*
CLWN 247	850.63**	0.30	0.32	-0.02	8.76**	5.38	0.04	0.29*	0.04	-0.19	-1.30
CLWN 341	20.45	2.44**	2.21	0.23	-2.00	-4.05	0.01	0.13	0.21	-0.19	-5.46**
CLWN 349	-121.26	0.78*	0.55	0.23	-5.45*	2.56	-0.03	-0.04	0.01	0.12	-1.65
CLWN 359	56.71	-0.14	-0.01	-0.13	-0.09	6.30	-0.02	-0.09	-0.07	-0.13	1.86
CLWN 364	574.61*	-0.45	-0.40	-0.05	1.36	5.47	0.05	-0.04	-0.07	0.12	-2.87*
CML 198/LPSC	-118.89	-0.09	-0.23	0.15	-5.00	-3.30	-0.02	0.18	0.04	0.37	3.69**
CML 254	-384.91	1.03**	0.74	0.29	5.26	-5.22	-0.08**	0.13	0.10	0.01	1.77
CML 395/CML 444	623.24**	-1.31**	-1.15**	-0.16	-0.19	-1.32	0.04	-0.37**	-0.21	-0.05	0.30
CML 442	-270.94	-0.89*	-0.82*	-0.08	-4.96	-7.39	0.02	-0.04	0.07	0.31*	3.70**
CML 444	-227.34	1.28**	1.35**	-0.08	9.07**	4.57	-0.02	0.04	-0.07	0.09	-2.59*
CML444/CML395/DTPWC8F31	-63.15	0.33	0.46	-0.13	-0.81	-5.24	-0.05	0.10	-0.10	0.12	-1.36
CML 494	460.67	0.00	-0.07	0.06	0.69	-0.25	0.07*	-0.04	-0.13	-0.30*	0.70
CZL 00001	464.90*	0.30	0.35	-0.05	-2.92	3.58	0.00	-0.07	-0.21	-0.10	-0.13
CZL 03007	-265.60	-0.39	-0.32	-0.08	-3.47	-3.53	0.00	0.04	0.04	-0.13	-1.20
CZL 068	258.83	-1.78**	-2.04**	0.26	10.62**	-9.70**	0.04	-0.26*	-0.21	0.01	1.93
CZL 0713	181.21	-0.97*	-0.84*	-0.13	8.59	2.14	0.04	-0.29**	-0.29**	-0.38**	4.00**
J-16-1	-129.98	-0.84*	-0.82*	-0.02	-2.31	3.90	-0.02	0.04	-0.02	0.11	1.94
Laposta Seq C7-F71-1-1-2	-426.49	-1.00*	-0.84*	-0.16	-3.77	-1.56	-0.01	-0.07	0.04	0.20	4.51**
M131	-154.23	0.83*	0.55	0.29	2.90	0.52	0.00	0.24*	0.04	0.26	0.87
P43SCRq Fs100-1-1-8	278.24	-0.03	0.21	-0.24	-0.55	5.62	0.01	-0.01	-0.07	-0.08	-2.68*
TZL Comp3	-652.06**	1.14**	1.18**	-0.05	-3.82	-12.50**	-0.04	0.18	0.18	0.17	-0.89
TZM501 × KU1414 × TZM501	-168.85	0.47	0.43	0.04	-4.87	-1.83	-0.03	0.27*	0.07	-0.13	-0.86
TZD II 134	117.69	-0.45	-0.32	-0.13	6.98*	5.91	-0.02	-0.09	0.07	-0.24	4.41**
TZD II 140	-108.01	-0.78*	-0.59	-0.19	-2.44	-0.79	0.04	-0.09	-0.07	-0.02	-0.11
TZD II 141	143.66	-0.20	0.05	-0.24	5.80*	8.32*	-0.02	0.07	0.07	-0.02	-1.63
TZD II 68	149.95	-1.86**	-1.73**	-0.13	-2.14	4.26	-0.02	-0.09	0.10	-0.16	-0.66
ZM 521B-66-4-1-1	-859.66**	-0.09	-0.29	0.20	-5.54*	-13.17**	-0.02	0.02	0.37**	0.42	1.05
ZM523B-29-2-1-1-B*6	-443.22	-0.34	-0.26	-0.08	0.03	-1.97	0.04	-0.09	0.18	0.26	2.08
SE	236.13	0.39	0.34	0.18	2.77	3.75	0.03		0.11	0.14	1.31

(Continued)

Table 6. (Continued.)

Line	GY (kg/ha)	DTS	DTA	ASI	EHT (cm)	PHT (cm)	EPP	SG	PASP	EASP	CC
Tester											
1368	-214.88*	-0.30	-0.16	-0.14*	-4.74**	-5.00**	-0.02	0.19	0.12	0.03	-0.46
9071	325.00*	1.45**	1.21	0.24**	5.82**	4.36**	0.00	-0.03	-0.04	-0.09	-2.47**
87036	-110.12	-1.15**	-1.05	-0.09	-1.08*	0.63	0.01	-0.16	-0.08	0.06	2.94**
SE	92.18	0.18	0.16	0.06	0.53	0.73	0.01	0.04	0.05	0.05	0.55

*, **Significant at 0.05 and 0.01 probability levels, respectively.

Table 7. Specific combining ability effects for grain yield across low N environments

Line	Testers		
	1368	9071	87036
CLRCW 36	-117.585	-12.068	129.653
CLWN 238	-564.686**	262.86	301.825
CLWN 240	89.3	-18.642	-70.657
CLWN 247	-110.216	105.063	5.153
CLWN 341	89.251	-382.466	293.215
CLWN 349	68.656	-233.335	164.679
CLWN 359	-403.486	497.053*	-93.566
CLWN 364	-305.534	113.98	191.554
CML 444/CML395/ DTPWC8F31	20.573	-203.678	183.105
CML 198/LPSC	294.811	37.096	-331.907
CML 254	-183.9	-221.86	405.759
CML 395/CML 444	123.6	-103.034	-20.566
CML 442	202.631	-169.719	-32.913
CML 444	-17.862	51.597	-33.735
CML 494	155.775	-41.537	-114.237
CZL 00001	126.995	273.339	-400.334
CZL 03007	335.762	-81.91	-253.852
CZL 068	419.436	-370.001	-49.436
CZL 0713	483.604*	-360.317	-123.286
J-16-1	34.14	117.361	-151.501
Laposta Seq C7-F18-3-2-1	19.625	100.734	-120.358
Laposta Seq C7-F71-1-1-2	349.008	-141.344	-207.665
M131	426.499*	-169.475	-257.024
P43SRCq Fs100-1-1-8	-208.056	320.697	-112.641
TZL comp 3	-564.846**	100.211	464.635*
TZM 501 × KU 1414 × 43 TZM501	-565.313**	522.52*	42.793
TZD II 134	-406.066	202.708	203.358
TZD II 140	77.859	68.762	-146.621
TZD II 141	-283.797	101.731	182.066
TZD II 68	537.606**	-432.119*	-105.488
ZM 521B-66-4-1-1	-238.822	-50.607	289.43
ZM523B-29-2-1-1-B*6	115.039	116.399	-231.438
SE	214	214	214

*, **Significant at 0.05 and 0.01 probability levels, respectively.

environments having longer vectors and were probably not strongly correlated with one another. Based on these requirements, KWH14, FUM14, FUMH14 and EJH14 with longer vectors and far away from the origin were more powerful in discriminating among the hybrids while FUM14 environment was the most representative. According to Yan and Tinker

Table 8. Specific combining ability effects for grain yield across high N environments

Line	Testers		
	1368	9071	87036
CLRCW 36	58.449	-502.388	443.939
CLWN 238	-265.197	300.303	-35.106
CLWN 240	-339.864	181.673	158.191
CLWN 247	0.786	-16.741	15.954
CLWN 341	205.775	260.781	-466.555
CLWN 349	-392.277	-233.888	626.164*
CLWN 359	596.705*	-88.117	-508.588
CLWN 364	-37.941	230.503	-192.561
CML 444/CML395/ DTPWC8F31	170.749	55.946	-226.695
CML 198/LPSC	-374.548	144.856	229.692
CML 254	-430.328	520.803	-90.475
CML 395/CML 444	367.267	-281.958	-85.309
CML 442	-89.267	-48.692	137.959
CML 444	-190.488	37.589	152.899
CML 494	657.519*	-209.327	-448.192
CZL 00001	-250.905	918.015**	-667.11*
CZL 03007	4.363	-302.461	298.098
CZL 068	384.591	-208.894	-175.697
CZL 0713	420.481	-567.462	146.98
J-16-1	-377.741	382.102	-4.361
Laposta Seq C7-F18-3-2-1	-176.831	821.15**	-644.319*
Laposta Seq C7-F71-1-1-2	-292.909	-462.029	754.938*
M131	-45.394	-174.545	219.939
P43SRCq Fs100-1-1-8	375.159	-474.243	99.085
TZL comp 3	-174.99	-60.502	235.493
TZM 501 × KU 1414 × 43 TZM501	133.179	-87.036	-46.142
TZD II 134	148.237	8.169	-156.406
TZD II 140	-89.399	419.609	-330.21
TZD II 141	-239.269	11.083	228.186
TZD II 68	536.957	-107.059	-429.898
ZM 521B-66-4-1-1	-303.576	-160.581	464.157
ZM523B-29-2-1-1-B*6	10.707	-306.658	295.951
SE	297.84		

*, **Significant at 0.05 and 0.01 probability levels, respectively.

(2006), an ideal test environment should effectively discriminate among genotypes and represent their mega-environment. Based on this criterion, FUM14 was identified as the ideal test environment. Also, EJH14 and KWH14 with long vectors and large angles could not be used in selecting superior hybrids, but could be used effectively in culling unstable genotypes.

Genotype-by-trait analysis of hybrids under low- and high-N conditions

Presented in Fig. 4 is the polygon view of the GT biplot analysis showing the best/worst hybrids for specific traits under low-N conditions. Principal component (PRC) 1 and PRC 2 jointly explained about 58% of the total variation among traits of the hybrids. In a sector, the vertex hybrid is considered the best/worst for traits within the sector. The figure revealed that entry 1 (CZL 0001 × 9071) was positioned at the vertex of the polygon for the sector containing GY, EHT, PLHT and EPP; 5 (CLWN 247 × 9071) for DP and DF; 28 (TZL Comp 3 × 1368) for PA, LS and ASI; 30 (ZM 521B-66-4-1-1 × 1368) for CA; 27 (Etubi) for SL; 16 (Laposta Seq C7-F71-1-1-2 × 87036) for CC and 6 (CZL 0713 × 87036) for RL. Similarly, Fig. 5 shows the polygon view of GT biplot analysis under high-N conditions. Both PRC 1 and PRC 2 accounted for 65% of the total variation among traits of the hybrids. Entry 1 (CZL 0001 × 9071) was at the vertex of the polygon in the sector that contains GY, EHT, PLHT and EPP; 9 for DF, DP and ASI; 30 for CA; 22 for SL and RL and 6 (CZL 0713 × 87036) for CC.

The biplot in Fig. 6 shows the relationships among agronomic traits of the hybrids under low soil nitrogen conditions. In the biplot, the line that connects a trait to the biplot origin is called a trait vector whereas the cosine of the angle between the vectors of a pair of traits is the genetic correlation coefficient between the two traits. Trait vectors at acute, right and obtuse angles indicate positive, weak or non-significant and negative genetic correlations, respectively. Thus, EPP, PLHT, EHT had a significant and positive genetic correlation with GY under low-N. Furthermore, PA, LS and CC were negatively correlated with GY whereas CA had a near-perfect negative linear relationship with GY. ASI, SL and RL had relatively short vectors, an indication of weak correlation with GY. Under high N, EPP, PLHT and EHT were positively correlated with GY although EHT had a relatively short vector (Fig. 7). High negative correlation was recorded between GY and each of PA, LS and CA while the correlations between GY and each of DF, DP, ASI and CC were weak.

Discussion

Genotype × environment effects were significant for most measured traits of the hybrids. This suggested that the performance of hybrids for most traits was not consistent across environments. These results are in agreement with the findings of Ifie (2013), Badu-Apraku *et al.* (2012, 2013a, b, c) and Noëlle *et al.* (2017) who reported significant genotype × environment interactions for maize grain yield and other agronomic traits under low N conditions. The GEI effects, however, were significant for only a few measured traits of the inbred lines suggesting that these lines responded similarly for most of the traits studied in the contrasting locations. Similar results were reported by Makumbi *et al.* (2011) who found significant GEI for only two traits under low N. The environment and genotype × environment interaction effects across environments were significant for most traits indicating that the individual environments were unique and that hybrid and inbred selection would not be consistent across the environments. Except for high N conditions, the ANOVA showed that the environment accounted for the largest sum of squares for grain yield followed by the GEI and the genotypes. The large environmental effects indicated that the test environments were highly variable thus substantiating the need for the testing of

Table 9. Grain yield and other agronomic traits of intermediate maturing maize hybrids (best 20 and worst 10) evaluated under low N environments in Fumesua, Ejura and Kwadaso in 2013 and 2014

Hybrids	GY (kg/ha)	DTS	DTA	ASI	PHT (cm)	EHT (cm)	EPP	SG	PASP	EASP	HC	CC	Base index	% Yield reduction
CLWN 247 × 9071	2596	59.96	58.43	1.53	156.91	93.48	0.92	3.37	2.66	2.01	2.58	16.58	10.53	44.00
ZM523B-29-2-1-1-B*6 × 9071	2680	59.54	57.51	2.03	173.94	85.81	0.83	3.26	2.68	2.29	2.73	20.17	8.12	17.83
TZDII 68 × 1368	2718	56.06	54.48	1.58	168.95	64.30	0.84	3.28	2.84	2.42	2.69	18.89	7.95	37.45
P43SCRq Fs100-1-1-8 × 9071	2523	61.27	59.05	2.22	180.26	86.79	0.76	2.96	2.63	2.43	2.46	17.41	6.83	33.31
CML 395/CML 444 × 87036	1869	56.54	54.53	2.01	164.05	75.80	0.72	2.59	2.37	2.34	2.23	23.32	6.63	54.56
TZM501 × KU1414 × TZM501 × 9071	2564	60.64	57.98	2.66	152.01	81.27	0.82	3.41	2.54	2.26	2.61	19.72	6.40	33.53
Laposta seq C7-F18-3-2-1 × 87036	1788	55.75	54.53	1.22	175.51	81.46	0.73	2.51	2.55	2.61	2.48	27.14	6.38	43.00
TZDII 68 × 87036	2304	56.25	54.02	2.23	176.59	73.07	0.73	2.71	2.48	2.77	2.48	20.58	5.84	33.27
CLWN 364 × 9071	2329	61.10	58.86	2.25	170.04	80.20	0.79	3.09	2.61	2.45	2.67	13.53	5.75	51.91
CZL 00001 × 9071	2355	61.27	58.50	2.76	170.61	79.25	0.71	3.07	2.29	2.50	2.49	22.77	5.45	55.96
CZL 0713 × 1368	2035	57.69	55.99	1.71	164.43	78.78	0.78	3.09	2.48	2.67	2.26	22.60	5.39	50.40
TZD II 134 × 87036	1941	58.06	56.24	1.82	176.53	87.06	0.82	3.04	2.55	2.59	2.34	24.87	5.27	47.02
CZL 068 × 1368	2127	57.32	55.31	2.01	149.71	63.50	0.69	2.73	2.64	2.43	2.59	23.26	5.25	47.72
Laposta Seq C7-F18-3-2-1 × 9071	2376	59.69	57.50	2.19	172.97	80.02	0.73	3.25	2.49	2.63	2.50	19.98	4.96	52.23
M131 × 1368*	2161	59.59	57.17	2.42	167.33	77.76	0.93	3.10	2.67	2.87	2.68	20.35	4.58	37.46
CLWN 359 × 9071	2463	60.57	58.30	2.27	167.03	78.58	0.66	3.28	2.55	2.44	2.70	15.67	4.50	39.74
CZL 03007 × 9071	1804	60.05	58.50	1.56	161.98	77.14	0.84	3.03	2.66	2.70	2.44	17.92	4.39	46.90
Laposta Seq C7-F71-1-1-2 × 9071	2073	59.28	56.70	2.58	178.42	86.98	0.69	2.98	2.34	2.56	2.39	20.68	4.11	33.21
Laposta Seq C7-F71-1-1-2 × 1368	2057	56.06	54.23	1.83	159.97	67.81	0.78	2.94	2.69	2.90	2.54	24.52	3.82	28.08
CML 395/CML 444 × 9071	2315	60.36	57.49	2.87	162.69	79.76	0.84	3.02	2.66	2.82	2.51	18.71	3.74	47.72
TZD II 140 × 87036*	1482	60.46	56.27	4.18	157.54	72.86	0.66	3.31	2.96	3.32	2.87	24.44	-5.45	54.16
CLWN 359 × 1368	1329	60.89	56.76	4.14	160.16	65.20	0.61	3.53	2.65	3.29	2.60	19.20	-5.74	69.22
CML 444/CML 395/ DTPWC8F31 × 1368	1308	61.92	57.93	3.98	152.61	69.87	0.63	3.70	2.85	3.22	2.77	17.77	-6.72	64.27
CML 254 × 1368	1116	62.13	57.50	4.64	158.46	79.13	0.61	3.61	2.75	2.79	2.61	20.20	-7.03	61.61
J-16-1 × 1368	1440	61.19	56.96	4.23	166.24	71.07	0.61	3.68	3.08	2.95	2.80	18.67	-7.11	49.05
TZD II 134 × 1368	1252	60.64	55.74	4.90	163.23	83.55	0.63	3.50	3.01	2.63	2.72	18.39	-7.18	66.54
TZD II 140 × 1368	1560	61.58	56.94	4.64	165.79	73.80	0.67	3.72	2.99	3.44	2.98	18.27	-7.97	53.51
CLRCW 36 × 1368	1074	63.14	58.67	4.47	164.86	76.95	0.57	3.31	2.83	3.23	2.64	16.80	-8.21	69.17

CLWN 238 × 1368	745	63.21	59.37	3.84	141.51	71.07	0.54	3.34	3.07	3.38	3.00	20.39	-10.83	77.51
TZL Comp3 × 1368	528	62.81	58.42	4.38	139.53	63.97	0.54	3.48	3.08	3.81	2.72	16.11	-15.02	80.24
Etubi - (Check)	1124	59.05	56.83	2.22	149.60	69.83	0.57	2.94	2.83	2.95	2.36	21.48	-5.22	64.29
1368 × 87036 (Check)	1462	61.76	57.09	4.67	157.80	73.18	0.57	3.27	2.75	3.04	2.68	18.75	-5.50	50.32
1368 × 9071 (Check)	1320	58.86	55.78	3.08	169.33	76.72	0.58	3.14	2.42	2.81	2.39	18.36	-3.93	59.06
87036 × 9071 (Check)	1876	58.46	57.01	1.45	162.80	80.73	0.67	3.02	2.37	2.99	2.43	20.41	3.59	47.27
Means	1784	59.55	57.10	2.44	164.23	77.59	0.71	3.19	2.69	2.87	2.61	19.40		
Max	2718	63.21	59.39	4.90	193.85	102.15	0.93	3.82	3.15	3.81	3.00	27.14		
Min	528	55.75	54.02	1.22	139.53	63.50	0.54	2.51	2.29	2.01	2.23	11.53		
SE	137	0.62	0.52	0.34	5.41	3.30	0.06	0.21	0.16	0.24	0.14	1.74		

GY, grain yield; DTS, days to silk; DTA, days to anthesis; ASI, anthesis silking interval; PHT, plant height; EHT, ear height; EPP, number of ears per plant; SG, stay green; PASP, plant aspect; EASP, ear aspect; HC, husk cover; CG, chlorophyll content.

genotypes in a wide range of sites over years as reported by Badu-Apraku *et al.* (2007) and Badu-Apraku and Lum (2010). Six hybrids: CZL 00001 × 9071, LapostaSEQC7-F18-3-2-1 × 9071, CLWN 364 × 9071, CLWN 247 × 9071, CML 395/CML 444 × 9071 and TZD II 68 × 1368 were identified among the 20 best hybrids under low N, high N and across environments. These hybrids had an inherent ability for outstanding performance under both low N and optimal conditions. Generally, farmers cultivate maize under varying soil fertility levels. In view of this, the high yield under low and high N conditions is desirable and these hybrids are appropriate for the test environments as they possess genes for general adaptation.

Under low N, the significant and positive GCA effects for grain yield were observed for the lines, CLWN 247, TZD II 68 and ZM523B-29-2-1-1-B*6 and the tester 9071. The contributions of tester and the lines demonstrate the high probability of contributing favourable alleles for superior yield performance to their progenies. Similarly, the significant and negative GCA effects observed for the stay green characteristic of CML 395/CML 444, CML 442, CZL 068, Laposta Seq C7-F71-1-1-2 and the tester 87036 indicated that these inbred lines would delay the senescence of their progenies and result in increased grain yield under low-N environments. Furthermore, the presence of significant GCA_i, GCA_t and SCA mean squares for all measured traits except the GCA_i for plant aspect and SCA for plant height, ears per plant, stay green characteristic, plant aspect, husk cover and chlorophyll content indicated that both additive and non-additive gene actions were important for most of the measured traits and that there was a scope for the improvement of the measured traits through selection under low N. The non-significant SCA mean squares for plant height, ears per plant, stay green characteristic, plant aspect, husk cover and chlorophyll content in the present study indicated that non-additive gene effects were not important in the inheritance of these traits. Badu-Apraku *et al.* (2013a, b, c) and Ifie (2013) also reported non-significant SCA for stay green characteristic under low N. The preponderance of GCA mean squares over SCA mean squares implied that additive gene action was more important than non-additive gene action for most measured traits and that GCA was the major component accounting for the differences among the hybrids under low N environments. This is consistent with other results (Below *et al.*, 1997; Kling *et al.*, 1997; Tamilarasi *et al.*, 2010; Ifie, 2013; Badu-Apraku *et al.*, 2013a, b, c). However, this is contradictory to the results of Betràn *et al.* (2003), Meseka *et al.* (2006), Makumbi *et al.* (2011), Meseka *et al.* (2013), Ndhlela (2012) and Noëlle *et al.* (2017) who reported preponderance of non-additive gene effects over additive gene effects for grain yield under low N. The differences in these results could be attributed to the differences in the germplasm used. The implication of these results is that there is a need for routine testing of newly developed inbred lines for combining ability in order to ensure good genetic gains from selection for improved tolerance to low N.

Under high N environments, GCA_i and GCA_t mean squares were significant for all the measured traits except for ears per plant. The SCA effects were significant for grain yield, days to silking and anthesis, anthesis-silking interval, plant aspect and husk cover. This indicated that both additive and non-additive gene action were important in the inheritance of grain yield and other traits across high N environments. The significant SCA effects observed for ears per plant were an indication that non-additive gene action was important in the inheritance of ears per plant under high N environments. This is consistent

Table 10. Grain yield and other agronomic traits of intermediate maturing maize hybrids (best 20 and worst 10) evaluated under high N environments in Fumesua, Ejura and Kwaadaso in 2013 and 2014

Hybrids	GY	DTS	DTA	ASI	PHT (cm)	EHT (cm)	EPP	SG	PASP	EASP	HC	CC
CZL 00001 × 9071	5348	59.99	57.49	2.50	194.86	95.05	0.76	2.44	2.24	2.20	2.48	27.56
Laposta Seq C7-F18-3-2-1 × 9071	4974	57.85	56.43	1.41	181.37	87.55	0.66	2.16	2.29	2.05	2.32	33.03
CLWN 364 × 9071	4844	57.65	56.05	1.60	186.11	92.06	0.64	1.96	1.99	2.19	2.01	26.24
CML 494 × 1368	4671	57.26	55.82	1.44	173.21	78.09	0.79	2.29	2.27	2.29	2.14	30.38
CLWN 247 × 9071	4636	58.66	56.70	1.96	184.28	98.57	0.75	2.83	2.27	2.17	2.24	27.78
CLWN 247 × 87036	4614	56.54	54.95	1.59	184.28	90.52	0.66	2.26	2.66	2.66	2.19	33.30
CLWN 247 × 1368	4507	57.86	56.37	1.49	179.15	96.80	0.67	2.68	2.28	1.94	2.34	31.05
CML 395/CML 444 × 9071	4428	56.84	54.97	1.87	177.85	91.59	0.66	2.06	2.23	2.60	2.54	27.66
CLWN 238 × 9071	4427	60.90	57.84	3.06	181.58	97.50	0.59	2.60	2.40	2.41	2.52	25.14
CML 395/CML 444 × 1368	4422	56.75	54.98	1.77	171.42	84.37	0.72	1.99	2.10	2.26	2.07	30.15
TZDII 68 × 1368	4344	55.16	53.20	1.96	185.17	78.74	0.60	2.38	2.16	2.27	2.21	31.80
CML 494 × 9071	4340	58.69	56.60	2.09	182.30	93.80	0.67	2.38	2.36	2.15	2.39	29.92
TZD II 140 × 9071	4327	57.47	55.61	1.86	181.59	91.25	0.60	2.32	2.34	2.40	2.80	27.32
CLWN 359 × 1368	4316	56.58	55.13	1.46	181.16	81.67	0.70	2.26	2.49	2.42	2.63	33.62
CML 198/LPSC × 9071	4255	58.87	56.94	1.94	182.78	89.56	0.70	2.54	2.24	2.20	2.11	33.01
CLWN 240 × 9071	4253	58.90	56.84	2.06	185.53	97.05	0.64	2.49	2.14	2.05	2.37	24.89
CML 444/CML 395/ DTPWC 8F31 × 9071	4228	58.86	57.09	1.77	181.79	93.90	0.65	2.28	2.03	2.46	2.05	25.62
P43SRCq Fs100-1-1-8 × 87036	4204	56.40	54.98	1.42	182.06	84.74	0.72	1.89	2.03	2.15	1.69	28.79
CML 254 × 9071	4193	59.64	57.47	2.18	177.77	100.44	0.67	2.22	2.45	2.33	2.38	33.61
CLWN 341 × 9071	4172	61.08	58.32	2.76	183.99	90.18	0.71	2.42	2.30	1.81	2.36	28.44
Laposta Seq C7-F71-1-1-2 × 9071	3105	57.96	55.94	2.02	184.53	90.36	0.62	2.57	2.49	2.91	2.77	33.38
CML 198/LPSC × 1368	3099	56.26	55.09	1.16	168.48	75.82	0.59	2.58	2.58	2.81	2.42	35.19
CLWN 359 × 87036	3056	56.76	55.13	1.62	176.53	79.91	0.58	2.23	2.45	2.20	2.72	34.62
ZM 521B-66-4-1-1 × 9071	2990	58.61	56.36	2.25	171.52	86.42	0.60	2.33	2.94	3.12	2.77	28.75
CML 254 × 1368	2907	57.82	56.15	1.67	171.11	85.11	0.53	2.73	2.53	2.15	2.03	33.86
Laposta Seq C7-F71-1-1-2 × 1368	2860	56.47	55.21	1.26	168.31	77.80	0.59	2.48	2.35	2.56	1.96	32.26
CLWN 349 × 1368	2837	57.83	55.99	1.84	182.81	78.95	0.59	2.42	2.30	2.48	2.36	32.74
J-16-1 × 1368	2825	55.60	53.86	1.74	171.07	78.31	0.57	2.91	2.77	2.79	2.90	33.46
TZL Comp3 × 1368	2673	59.26	57.56	1.70	145.54	69.35	0.54	2.91	3.20	3.01	3.25	28.34
ZM 521 B-66-4-1-1 × 1368	2340	57.61	55.65	1.96	157.75	77.86	0.54	2.45	2.84	3.11	2.68	33.12
Checks												
87036 × 9071	3558	57.53	55.32	2.21	177.30	88.54	0.58	2.51	2.31	2.76	2.33	30.86
Etubi – (Check)	3149	56.29	54.87	1.42	164.10	74.63	0.56	2.26	2.74	3.24	2.61	36.69
1368 × 87036	2942	56.94	55.12	1.82	173.64	84.87	0.55	2.51	2.53	2.94	2.34	31.61
1368 × 9071	3225	58.50	56.16	2.34	177.17	84.50	0.59	2.22	2.25	2.35	2.31	32.74

(Continued)

Table 10. (Continued.)

Hybrids	GY	DTS	DTA	ASI	PHT (cm)	EHT (cm)	EPP	SG	PASP	EASP	HC	CC
Means	3713	57.42	55.64	1.76	177.86	86.77	0.65	2.35	2.35	2.45	2.34	31.22
Max	5348	61.08	58.32	3.06	196.12	105.06	0.87	2.91	3.20	3.24	3.25	31.22
Min	2340	54.34	52.62	0.85	145.54	69.35	0.53	1.83	1.85	1.81	1.69	22.12
SE	284	0.54	0.44	0.29	4.75	3.55	0.06	0.16	0.16	0.23	0.16	2.05

GY, grain yield; DTS, days to silk; DTA, days to anthesis; ASI, anthesis silking interval; PHT, plant height; EHT, ear height; EPP, number of ears per plant; SG, stay green; PASP, plant aspect; EASP, ear aspect; HC, husk cover; CC, chlorophyll content.

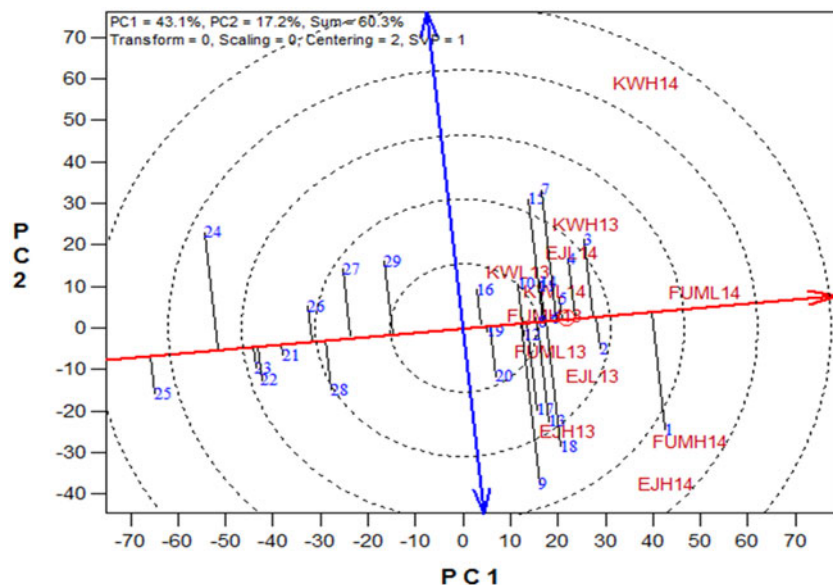


Fig. 1. Colour online. Performance and stability of 29 intermediate maturing maize hybrids across low and high N environments in 2013 and 2014. EJA14, Ejura high 2014; EJA14, Ejura low 2014; EJA13, Ejura high 2013; EJA13, Ejura low 2013; FUMH13, Fumesua low 2013; FUMH13, Fumesua high 2013; FUML14, Fumesua low 2014; FUMH14, Fumesua high 2014; KWL13, Kwadaso low 2013; KWH13, Kwadaso high 2013; KWH14, Kwadaso high 2014; KWL14, Kwadaso low 2014.

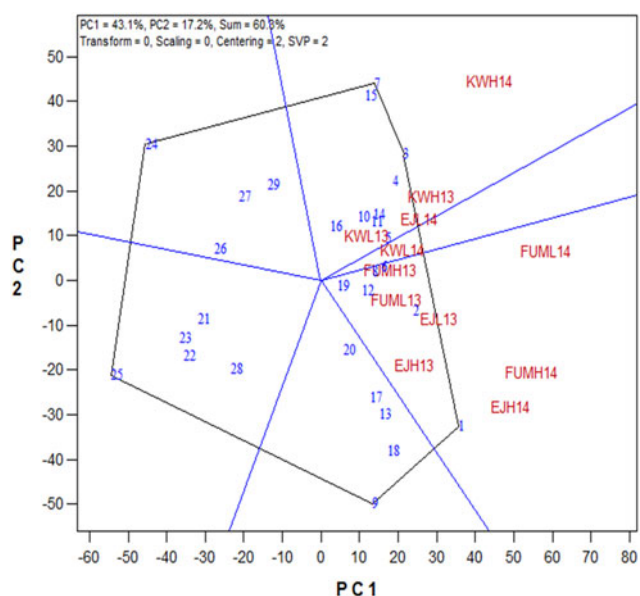


Fig. 2. Colour online. A 'which won where' GGE biplot of grain yield of 29 intermediate maturing maize hybrids evaluated across low N and high N environments in 2013 and 2014. EJA14, Ejura high 2014; EJA14, Ejura low 2014; EJA13, Ejura high 2013; EJA13, Ejura low 2013; FUMH13, Fumesua low 2013; FUMH13, Fumesua high 2013; FUML14, Fumesua low 2014; FUMH14, Fumesua high 2014; KWL13, Kwadaso low 2013; KWH13, Kwadaso high 2013; KWH14, Kwadaso high 2014; KWL14, Kwadaso low 2014.

with the findings of Ifie (2013). The preponderance of GCA mean squares over SCA mean squares implied that additive gene action was more important than non-additive gene action for most measured traits and that GCA was the major component accounting for the differences among the single cross hybrids. With preponderance of GCA over SCA variance, early generation testing may be more effective and promising hybrids could be identified and selected mainly based on the prediction from GCA effects.

In order to identify maize cultivars with stable and high yield performance under low N as well as under high N conditions for commercialization, the GGE biplot was adopted to decompose the GEI. For a hybrid to be released and commercialized, it must demonstrate both high average yield performance and high stability across locations (Kaya *et al.*, 2006; Yan and Tinker, 2006; Jalata, 2011; Badu-Apraku *et al.*, 2011a,b). Crop breeders work to develop cultivars that have high yield in various agro-climatic conditions, and the most adapted cultivars created in the areas of their cultivation (Anuarbek *et al.*, 2019). The most stable hybrids in this study were CML 494 × 1368 (12), TZD II 134 × 9071 (8), CML 395/CML 444 × 9071 (6) and TZD II 68 × 1368 (5). These hybrids should be selected for further testing across multiple locations to confirm the consistency of performance and commercialized.

Badu-Apraku and Lum (2010) reported that farmers in West Africa are slow in adopting stress-tolerant maize hybrids and open-pollinated varieties. He attributed this to the erroneous

Fig. 3. Colour online. The ‘discriminating power and representativeness’ view of GGE biplot on a genotype × environment yield data of 29 intermediate maturing maize hybrids evaluated in 12 environments. EJH14, Ejura high 2014; EJL14, Ejura low 2014; EJH13, Ejura high 2013; EJL13, Ejura low 2013; FUML13, Fumesua low2013; FUMH13, Fumesua high 2013; FUML14, Fumesua low 2014; FUMH14, Fumesua high 2014; KWL13, Kwadaso low 2013; KWH13, Kwadaso high 2013; KWH14, Kwadaso high 2014; KWL14, Kwadaso low 2014.

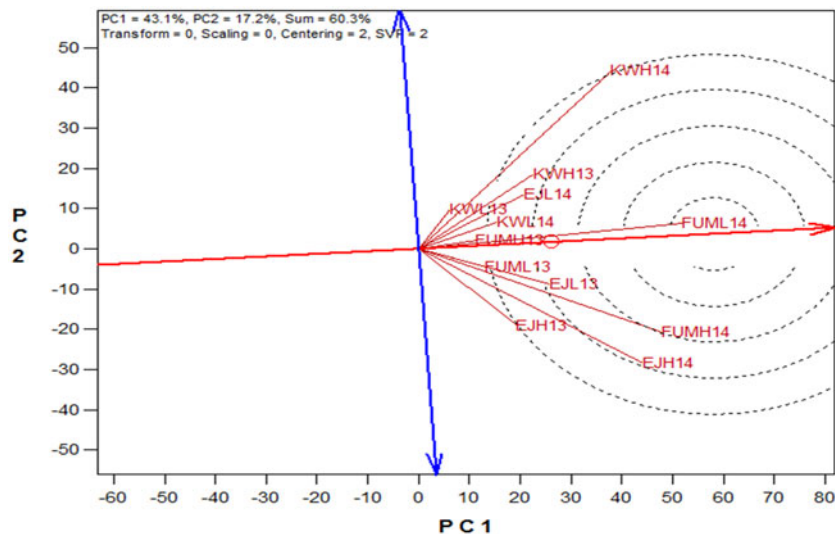
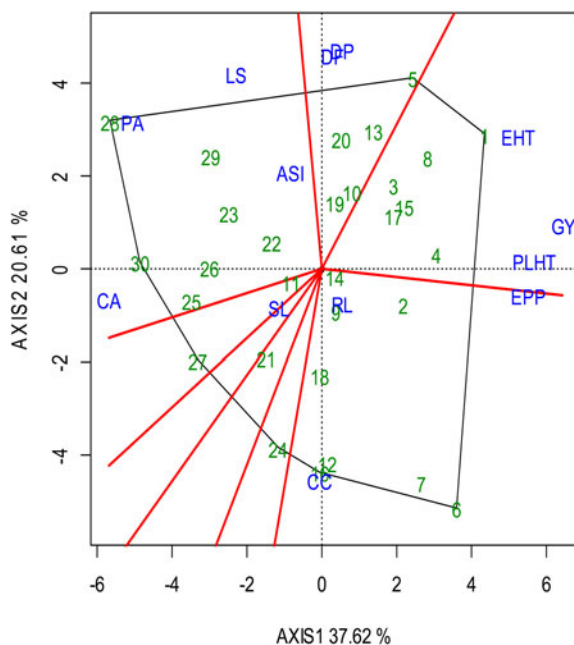


Fig. 4. Colour online. Polygon view of genotype-by-trait biplot of 13 traits of 30 selected intermediate maturing maize hybrids evaluated under low N conditions at three locations during 2013 and 2014 growing seasons. GY, grain yield; PLHT, plant height; EHT, ear height; EPP, number of ears per plant; RL, root lodging; SL, stalk lodging; CC, chlorophyll content; CA, cob aspect; PA, plant aspect; LS, leaf senescence; DP, days to pollen; DF, days to flowering; ASI, anthesis-silking interval.



No	Genotype
1	CZL 0001 X 9071
2	CML 494 X 1368
3	CLWN 247 X 1368
4	Laposta Seq C7-F18-3-2-1 X 9071
5	CLWN 247 X 9071
6	CZL 0713 X 87036
7	CML 395/ CML 444 X 87036
8	TZd II 141 X 9071
9	P43SCRq Fs100-1-1-8 X 1368
10	CLWN 364 X 1368
11	CZL 00001 X 1368
12	CZL 068 X 87036
13	CML 254 X 9071
14	CML 395/ CML 444 X 9071
15	CZL 0713 X 9071
16	Laposta Seq C7-F71-1-1-2 X 87036
17	TZd II 134 X 9071
18	CZL 00001 X 87036
19	TZd II 134 X 1368
20	TZL Comp3 X 9071
21	CML 198/ LPSC X 87036
22	CLWN 349 X 1368
23	CML 254 X 1368
24	Laposta Seq C7-F18-3-2-1 X 87036
25	J-16-1 X 1368
26	1368 X 87036
27	Eubi - (Check)
28	TZL Comp3 X 1368
29	ZM 521B-66-4-1-1 X 9071
30	ZM 521B-66-4-1-1 X 1368

perception that maize genotypes selected under stress environments might be adapted to the stress environments and that such genotypes would produce less yield in stress-free environments. Consequently, high yielding hybrids selected in both low- and high-N environments are desirable. The result of the present study revealed that hybrid CZL 0001 × 9071 because of its elevated grain yield, increased number of ears per plant, desirable ear and plant heights under both low- and high-N conditions was the highest yielding under each of the two research conditions. Hybrids with high values for such traits as DP, DF, PA, CA, ASI, LS, RL and SL were not agronomically desirable and were thus considered inferior. For instance, hybrid CLWN 247 × 9071 was the vertex hybrid for the sector containing DP and DF. This indicated that this hybrid was the latest to reach

anthesis and silking whereas TZL Comp 3 × 1368 and ZM 521B-66-4-1-1 × 1368 were the vertex hybrids for sectors containing PA and CA, respectively. These hybrids were therefore considered susceptible to low-N conditions.

Breeders and geneticists require precise information on inter-relationships among agronomic traits, including grain yield for significant genetic gains from selection (Badu-Apraku *et al.*, 2013a, b, c). Therefore, one of the important objectives of the present study was to identify appropriate secondary traits for selecting for high grain yield in intermediate maturing maize under low- and high-N conditions. The relatively short trait vectors observed for SL, RL and ASI under low-N conditions indicated that these traits were not important in selecting intermediate maturing maize hybrids for tolerance to low-N. This result is

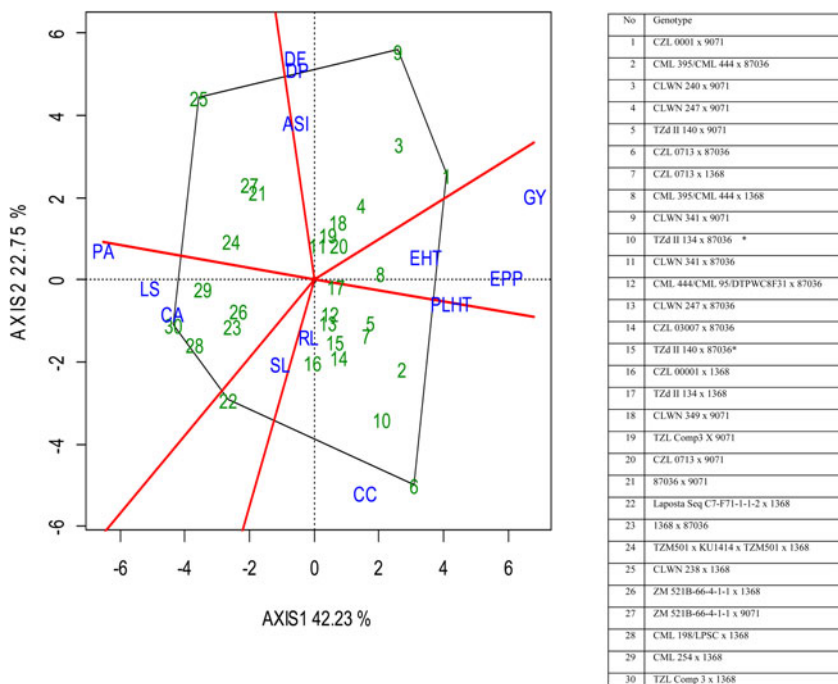


Fig. 5. Colour online. The ‘which-won-where’ of genotype by trait interaction biplot of 13 traits of 30 selected intermediate maturing maize hybrids evaluated under high-N conditions at three locations during 2013 and 2014 growing seasons. GY, grain yield; PLHT, plant height; EHT, ear height; EPP, number of ears per plant; RL, root lodging; SL, stalk lodging; CC, chlorophyll content; CA, cob aspect; PA, plant aspect; LS, leaf senescence; DP, days to pollen; DF, days to flowering; ASI, anthesis-silking interval.

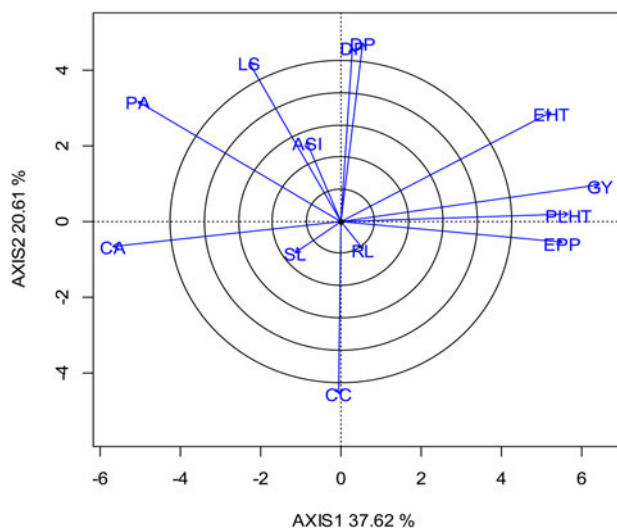


Fig. 6. Colour online. A vector view of the genotype-by-trait biplot showing interrelationships among traits of 30 selected intermediate-maturing maize hybrids evaluated under low-N conditions at three locations during (2013 and 2014) growing season. GY, grain yield; PLHT, plant height; EHT, ear height; EPP, number of ears per plant; RL, root lodging; SL, stalk lodging; CC, chlorophyll content; CA, cob aspect; PA, plant aspect; LS, leaf senescence; DP, days to pollen; DF, days to flowering; ASI, anthesis-silking interval.

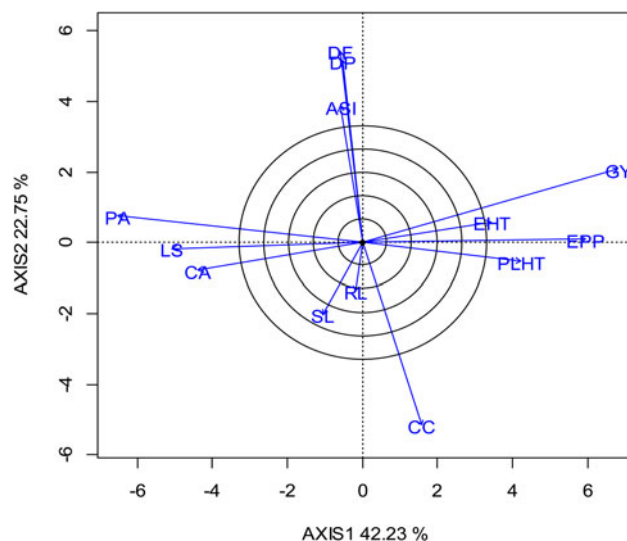


Fig. 7. Colour online. A vector view of the genotype-by-trait biplot showing interrelationships among traits of 30 selected intermediate-maturing maize hybrids evaluated under high-N conditions at three locations during (2013 and 2014) growing season. GY, grain yield; PLHT, plant height; EHT, ear height; EPP, number of ears per plant; RL, root lodging; SL, stalk lodging; CC, chlorophyll content; CA, cob aspect; PA, plant aspect; LS, leaf senescence; DP, days to pollen; DF, days to flowering; ASI, anthesis-silking interval.

inconsistent with the findings of Badu-Apraku *et al.* (2018). The significant genetic correlations recorded between GY and PLHT, EPP, EHT, CA and PA implied that the improvement of these traits would lead to significant gains in grain yield under low-N conditions. Badu-Apraku *et al.* (2018) reported similar findings. The authors indicated that PA, CA, PLHT, SL and DF were more appropriate selection criteria for improving grain yield in early maturing maize under low-N conditions. However, EHT was not identified as a selection criterion in their study. The

differences in the results of the two studies were attributable to the differences in the genetic materials used for the studies. Similarly, the strong inter-trait relationship observed between GY and EPP, PLHT, CA, PA as well as LS under high-N conditions indicated that these traits have significant direct and indirect effects on grain yield under high-N conditions and would therefore be effective for selecting for improved grain yield under high-N. Additionally, the identification of CA, PA, PLHT and

EPP as selection indices under the two N environments suggested that these traits could be employed for simultaneous improvement of grain yield under the contrasting growing conditions. The high and positive genetic correlation between DP and DF under low-N, as well as DF, DF and ASI under high-N conditions implied that either of the traits would suffice for field evaluations of intermediate maturing maize, thus reducing the time and resources spent assaying traits in field trials, without sacrificing precision. It is surprising to note that chlorophyll content, the green pigment in leaves, which is vital for photosynthesis in plants, had weak correlations with GY under both low- and high-N conditions. The plausible explanation for this is that the chlorophyll content of the leaves of the maize plants under the research conditions, low-N in particular, might have been above the critical minimum below which, photosynthetic activities could have been impaired.

Conclusion

The hybrids CML 494 × 1368, TZD II 134 × 9071, CML 395/CML 444 × 9071 and TZDII 68 × 1368 were identified as the highest yielding and most stable. The significant and positive GCA effects observed for grain yield of inbreds CLWN 247, TZD II 68, ZM523B-29-2-1-1-B*6 and the tester 9071 under low-N environments indicated that the inbreds are invaluable resource for breeding for low-N tolerant hybrids as well as for introgression into tropical maize populations. Additionally, the preponderance of GCA mean squares over SCA mean squares implied that additive gene action was more important than the non-additive for most measured traits under low N environments. Finally, the strong inter-trait relationship observed between GY and EPP, PLHT, CA, PA as well as LS under high-N conditions indicated that these traits have significant effects on grain yield under high-N conditions and would be effective for selecting for improved grain yield.

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Conflict of interest. The authors declare there are no conflicts of interest.

Ethical standards. Not applicable.

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Appendix: List of rainfall and temperature figures for 2013 and 2014

Council for Scientific and Industrial Research – Crops Research Institute, Library Material, 2015

Year	Parameter	2013	2014
JAN	Rainfall	0.0	17.8
	Min temp	21.5	22.9
	Max temp	34.0	32.6
FEB	Rainfall	13.7	23.2
	Min temp	23.7	22.6
	Max temp	35.2	33.2
MAR	Rainfall	13.5	13.4
	Min temp	23.5	23.1
	Max temp	33.1	33.4
APRIL	Rainfall	16.8	9.6
	Min temp	23.5	22.9
	Max temp	33.2	33.3
MAY	Rainfall	12.2	9.0
	Min temp	22.7	23.1
	Max temp	31.6	31.7
JUN	Rainfall	9.6	15.8
	Min temp	22.6	23.1
	Max temp	30.0	30.4
JUL	Rainfall	9.2	7.2
	Min temp	21.9	22.2
	Max temp	28.3	28.7
AUG	Rainfall	0.8	4.9
	Min temp	21.5	21.8
	Max temp	27.7	28.0
SEPT	Rainfall	11.6	6.6
	Min temp	22.1	22.4
	Max temp	29.6	29.2
OCT	Rainfall	11.7	15.0
	Min temp	22.2	22.5
	Max temp	30.7	31.0
NOV	Rainfall	11.5	14.7
	Min temp	22.9	22.9
	Max temp	31.5	31.7
DEC	Rainfall	14.0	1.6
	Min temp	21.5	22.4
	Max temp	31.4	32.3