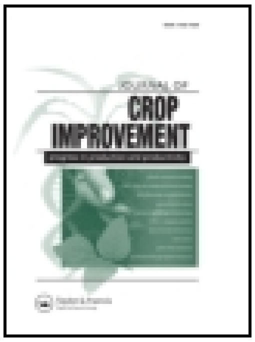

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Effects of drought stress on grain yield, agronomic performance, and heterosis of marker-based improved provitamin-A maize synthetics and their hybrids

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ABSTRACT

Provitamin A-enriched maize (*Zea mays* L.) is an important complementary food staple for combating vitamin A deficiency (VAD) in high maize-producing and maize-consuming countries of sub-Saharan Africa (SSA). However, frequent drought is a major abiotic factor that retards maize growth, resulting in yearly fluctuations in grain yield. Development of provitamin A-enriched maize varieties resilient to recurrent drought stress could enhance and stabilize maize grain yield. This study was conducted to assess the effects of managed drought stress (MDS) on the performance and heterosis of some marker-based improved provitamin A maize synthetics and their varietal-cross hybrids. The maize synthetics and their varietal-cross hybrids, along with a drought-tolerant check (PVASYN13), were evaluated under MDS and well-watered (WW) conditions at Ikenne, Nigeria, for two years. Genotype and year effects were significant for grain yield and some agronomic traits under MDS and WW conditions. Grain yield was reduced by 56% under MDS. Grain yield was significantly correlated with days to anthesis, days to silking and anthesis-silking-interval under MDS but not under WW condition. Under MDS, three varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, PVASYNHGBC0/ PVASYNHGAC1) had similar grain yields and tolerance indices as the drought-tolerant check, whereas PVASYNHGBC1/PVASYNHGAC2 produced 12.5% more grain yield than the check. Three of the varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1 and PVASYNHGBC1/PVASYNHGAC2) had significant mid-parent heterosis for grain yield under the two test conditions, and were recommended for developing drought-tolerant varieties to combat VAD in drought-prone environments of SSA.

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KEYWORDS
Grain yield; heterosis; maize synthetics; managed drought stress; varietal-cross hybrids

Introduction

Maize (*Zea mays* L.) is an important staple food crop and nutrient source for most people in sub-Saharan Africa (SSA) (Nuss and Tanumihardjo 2010;

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Mengesha et al. 2019). Yellow and orange maize naturally accumulate provitamin A carotenoids and thus are targeted for improvement in breeding programs to combat vitamin A deficiency (VAD), which is prevalent in SSA. The kernels of maize cultivars commonly grown and consumed in SSA contain less than 2 μg g^{-1} of provitamin A (Pixley et al. 2013), which is insufficient to meet the recommended daily allowance in a diet (Institute of Medicine 2012). Steady decline in yield and production of maize in the region as a result of drought stress further exacerbates the problem (FAOSTAT 2018). Therefore, deployment of climate-resilient varieties with high grain yield, good agronomic performance, moderate to high provitamin A content will be a good approach to obtaining provitamin A-enriched maize in areas with increasing effects of drought stress.

Drought stress occurs when available water in the soil is reduced and atmospheric conditions cause continuous loss of water by transpiration or evaporation. Under drought stress, there is insufficient soil moisture for plants to drive their physiological and biochemical functions, thereby leading to leaf senescence and decreased photosynthesis (Jain, Hirve, and Prajapati 2019). When drought occurs during flowering of maize, it disrupts fertilization and diminishes availability of photosynthate to developing kernels, leading to kernel abortion, reduction in kernel number, and a yield loss ranging from 17% to 60% (Edmeades et al. 1999; Cattivelli et al. 2008; Aslam, Maqbool, and Cengiz 2015). Furthermore, drought stress coinciding with both flowering and grain-filling stages of maize could result in yield losses of up to 90% (Menkir and Akintunde 2001; Meseka, Menkir, and Ajala 2011).

Globally, about 160 million hectares of maize is grown under rain-fed conditions, and is thus subject to random drought stress (Edmeades 2013). The rapid change in weather patterns, the projected rising temperatures and uncertainties in rainfall patterns associated with the current trend of climate change will further heighten the intensity and frequency of drought in many parts of Africa, including the corn belt of Nigeria (Badu-Apraku et al. 2011a; FAO 2013; Masih et al. 2014; Shiferaw et al. 2014). Therefore, enhancing food security and farmers' livelihoods in SSA require an improvement in the resilience of crops to drought (Menkir et al. 2020).

Most maize biofortification programs focus on the improvement of provitamin A (PVA) content and other micronutrients, with little or no consideration for the crop's tolerance to abiotic stresses. To promote farmers' adoption of biofortified maize, varieties with enhanced provitamin A content should combine high yield potential with stable performance across a broad range of growing conditions (Mengesha et al. 2019). Maize breeders at the International Institute of Tropical Agriculture (IITA), Ibadan, have developed two marker-based provitamin A-enriched maize synthetics (HGA and HGB) belonging to different heterotic groups (Astatke 2018; Iseghohi et al.

2020). The maize synthetics, their selection cycles and varietal-cross hybrids were evaluated across eight environments in Nigeria and were found to be stable in grain yield and content of major carotenoids (Iseghohi et al. 2020). However, their responses under drought stress have not been evaluated. Although several studies (Gage et al. 2017; Kusmec, Leon, and Schnable 2018) have shown that maize genotypes found adaptive to multi-environments could be tolerant to abiotic stresses, such as drought, other findings show that genotypes improved for nutritional qualities could have low tolerance to drought stress (Aslam, Maqbool, and Cengiz 2015; Barutcular et al. 2016). Assessment of the effects of drought stress on grain yield and agronomic performance of provitamin A-enriched maize genotypes will elicit their responses to water-deficit conditions.

One of the most efficient strategies for breeding drought-tolerant maize is to manage stress in experimental trials, partly or entirely, in a dry season through irrigation system (Bänziger et al. 2000, 2006). Exposure of breeding materials to moisture deficit at anthesis and grain filling stages, with resultant yield losses of 40–90%, has been utilized for developing drought-tolerant maize germplasm (Heisey and Edmeades 1999). Secondary traits highly correlated with grain yield and possessing high heritability under deficit-moisture stress are often used as selection criteria for drought tolerance (Bänziger et al. 2006; Araus, Serret, and Edmeades 2012). Traits such as days to anthesis and silking, anthesis-silking interval (ASI), and stress tolerance index (STI) have been used to select drought-tolerant genotypes, because of the low heritability of grain yield under drought stress (Fernandez 1992; Mitra 2001; Araus, Serret, and Edmeades 2012; Kondwakwenda et al. 2019).

Several studies have reported significant reduction in grain yield of maize under drought stress (Adebayo et al. 2014; Meseka, Menkir, and Obeng-Antwi 2015; Abdulmalik et al. 2017; Menkir et al. 2020), but there is limited information on the effects of drought stress on grain yield and agronomic performance of provitamin A-enriched maize. In a study involving 30 provitamin A-enriched hybrids, Manjeru (2017) reported an average grain yield of 1.39 t/ha under drought stress and a 78% yield reduction across two different environments. Similarly, Ortiz-Covarrubias et al. (2019) evaluated 55 provitamin A maize hybrids under drought stress and reported a 79% yield reduction. However, Kondwakwenda et al. (2019) reported a relatively lower yield loss of 51.2% under drought stress among 46 provitamin A maize inbred lines evaluated across four environments in South Africa. Assessment of parental synthetics originally improved for provitamin A and their varietal-cross hybrids under drought stress should provide information on their responses and heterosis of the hybrids under moisture-deficit conditions. Therefore, the objectives of this study were to

(i) evaluate the effects of drought stress on grain yield and agronomic performance of two provitamin A-enriched maize synthetics, their selection cycles and varietal-cross hybrids
(ii) assess the effect of drought stress on heterosis of varietal-cross hybrids and
(iii) investigate the relationships between grain yield and secondary traits under drought stress.

Materials and methods

Genetic materials and field evaluation

The genetic materials (hereafter referred to as genotypes) used in this study comprised two maize synthetics belonging to different heterotic groups (HGA and HGB), selection cycles C0 to C2, nine varietal-cross hybrids, and a released drought-tolerant PVA-enriched check (PVASYN13) (Table 1). The varietal-cross hybrids were generated from the crosses of the selection cycles of the two groups using North Carolina Design II. Detailed description of the procedure used in developing the genotypes at the Maize Improvement Program of the International Institute of Tropical Agriculture (IITA), Ibadan, has previously been described in Iseghohi et al. (2020).

The genotypes were evaluated for grain yield and agronomic performance under managed drought stress (MDS) and fully irrigated conditions,

Table 1. The provitamin A and total carotenoid contents of two maize synthetics, their selection cycles, varietal- crosshybrids, and a drought-tolerant check variety included in the present study.

S/N	Pedigree	Provitamin A (μg/g)	Total carotenoid (μg/g)
	Parental synthetics		
1	PVASYNHGAC0	6.9	24.6
2	PVASYNHGAC1	7.0	25.6
3	PVASYNHGAC2	9.0	28.3
4	PVASYNHGBC0	8.4	29.1
5	PVASYNHGBC1	6.9	24.5
6	PVASYNHGBC2	8.2	29.4
	Varietal crosses		
7	PVASYNHGBC0/PVASYNHGAC0	8.0	27.3
8	PVASYNHGBC1/PVASYNHGAC0	6.6	24.8
9	PVASYNHGBC2/PVASYNHGAC0	7.4	28.1
10	PVASYNHGBC0/PVASYNHGAC1	7.9	27.7
11	PVASYNHGBC1/PVASYNHGAC1	6.9	26.0
12	PVASYNHGBC2/PVASYNHGAC1	7.2	26.4
13	PVASYNHGBC0/PVASYNHGAC2	9.0	29.3
14	PVASYNHGBC1/PVASYNHGAC2	7.7	25.6
15	PVASYNHGBC2/PVASYNHGAC2	8.4	29.7
16	PVASYN13 (Check)	8.6	30.1

hereafter known as well-watered (WW) condition at the IITA experimental station, Ikenne (6°54′N, 3°42′E, 60 masl), during the 2018/2019 and 2019/2020 dry seasons (December to March). The soil at Ikenne is eutric nitosol (FAO classification) and the topography of the experimental field is flat and uniform. In each year, the genotypes were planted in two blocks, with one block well-watered, while the other was subjected to MDS. The two blocks were separated by a distance of 20 m to avoid underground seepage and lateral movement of water from the WW block to the MDS block. The WW block received full irrigation every week using a sprinkler irrigation system from planting till physiological maturity. In the managed-drought plots, irrigation was withdrawn five weeks after planting to impose drought stress two weeks before flowering until harvesting. The trials were arranged in a 4 × 4 randomized incomplete block design with four replicates. Plots consisted of two rows 4 m long with inter- and intra- row spacing of 0.75 m and 0.5 m, respectively. Three seeds were planted and seedlings were thinned to two per hill two weeks after emergence. Fertilizer was applied following the recommendation of Chude et al. (2012) based on a soil test. Fertilizer in the form of NPK (15:15:15) was applied at the time of sowing at the rate of 400 kg/ha to supply 60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. This was top-dressed with 60 kg N ha^{-1} urea four weeks after planting. Weeds were controlled with the application of 500 g/L of atrazine and 200 g/L of paraquat as pre- and post-emergence herbicides, respectively, which was complemented with hand weeding to keep the plots weed-free.

Data collection

Under each water regime, days to anthesis (DA) and days to silking (DS) were recorded as number of days from planting to when 50% of the plants in a plot shed pollen and had emerged silks, respectively. Anthesis-silking interval (ASI) was calculated as the difference between DS and DA. Plant height (PHT) and ear height (EHT) were measured in cm as the distance from the base of the plant to first tassel branch and the node bearing the upper ear, respectively. Plant aspect (PASP) was scored on a 1 to 5 scale, where 1 represented uniform, clean, vigorous, and good overall phenotypic appeal, and 5 represented weak, diseased, and poor overall phenotypic appeal. All ears were harvested per plot and ear aspect (EASP) scored on a 1 to 5 scale, where 1 represented clean, well-filled, uniform, and large ears, and 5 represented diseased, poorly filled, variable, and small ears. Ears were harvested on a plot basis, shelled and the grain moisture content measured using a portable Dickey-John moisture tester. The grain weight and moisture content were used to compute grain yield adjusted to 15% moisture. Stress tolerance index (STI) was estimated for the MDS trial based on the formula of Fernandez (1992) as follows:

$$STI = \frac{GYi(n) \times GYi(s)}{GY^2}$$

where GYi(n) and GYi(s) represented grain yields of genotype i under well-watered and under drought-stress conditions, respectively; GY was the mean grain yield of all genotypes under well-watered condition. Weather data comprising rainfall, temperature, relative humidity and solar radiation were recorded throughout the growing seasons.

Statistical analyses

Analysis of variance (ANOVA) was conducted for drought stress and well-watered trials, respectively, using PROC MIXED procedure in SAS version 9.4 (SAS Institute 2012). Genotype was considered as fixed effect, whereas year, and the nested effects as random factors. Means were separated using the least significant difference (LSD) at 0.05 level of probability. Broad-sense heritability for each trait was estimated using PROC MIXED procedure in SAS as described by Holland et al. (2003). Mid-parent heterosis (MPH) and better-parent heterosis (BPH) were estimated in Analysis of Genetic Design (AGD-R) according to the formulae of Falconer and Mackay (1996) as:

$$MPH = \frac{F1 - MP}{MP} \times 100$$

,

$$BPH = \frac{F1 - BP}{BP} \times 100$$

where, F_1, MP, and BP are the means of hybrids, mid-parents, and better-parents. Significance of heterosis was tested with the t-statistic. Pearson correlation coefficient (r) among traits was calculated using PROC CORR in SAS (SAS Institute 2012).

Results

Weather conditions during the trials

Monthly weather conditions recorded during the trials showed that it was suitable to adequately evaluate maize genotypes under managed drought stress (Figure 1a and Figure 1b). Although there was some rainfall during field evaluations in 2018/2019, it did not alter the effect of drought stress on maize genotypes. Mean minimum and maximum temperatures in both years were ideal for normal growth and development of maize. At anthesis, solar radiation was higher in 2018/2019 than in 2019/2020 season.

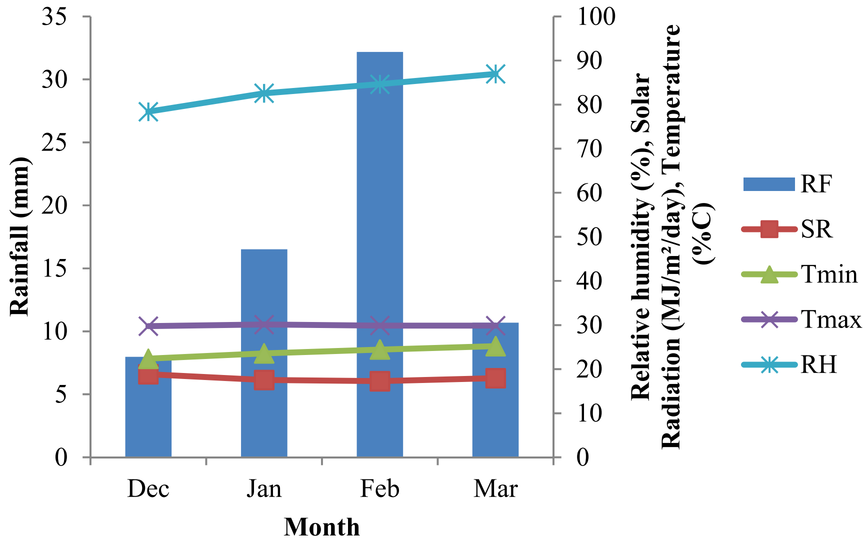
Genetic variation among the genotypes

In the ANOVA of each water regime, the effect of year was significant for grain yield and all or most agronomic traits (Table 2). The genotypes differed significantly for grain yield, days to silking, anthesis-silking interval, and stress-tolerance index under MDS. Under WW condition, significant differences were observed for grain yield, days to anthesis and silking, plant height, and ear aspect. The interaction between genotype and year was significant for grain yield under MDS condition.

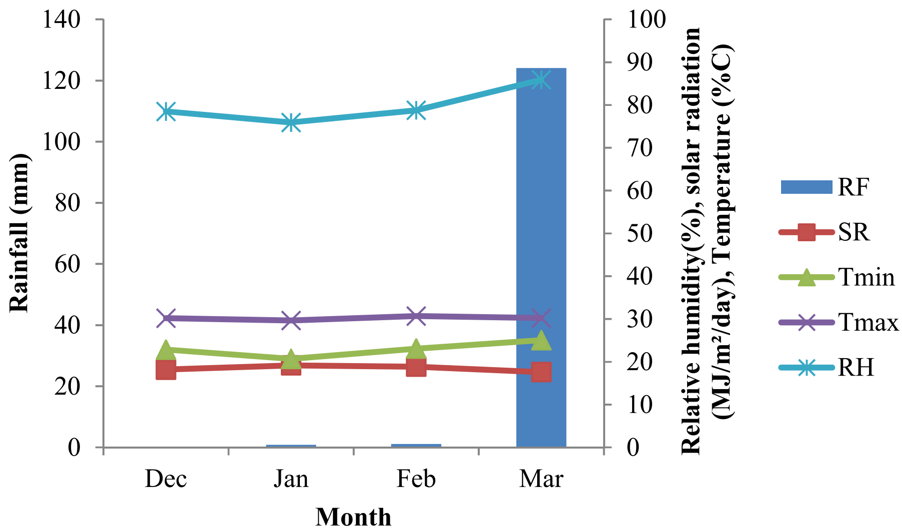
Agronomic performance of provitamin A maize synthetics, their selection cycles and hybrids under managed drought stress and well-watered condition

Drought stress reduced grain yield and agronomic performance of the genotypes. Grain yield under managed drought stress was 44% of the yield under well-watered condition, resulting in a relative yield reduction of 56% (Table 3).

There was no marked difference in the mean grain yield performance among the parental synthetics under managed drought stress, which were significantly lower than that of the drought-tolerant check variety (Table 3). However, the grain yield and other agronomic traits of three of the varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, and PVASYNHGBC0/PVASYNHGAC1) were comparable with those of the check variety. One hybrid (PVASYNHGBC1/PVASYNHGAC2) produced 12.5% more yield than the check variety under managed drought stress condition. These four hybrids had moderate to high STI. Under well-watered condition, all the parental synthetics had similar grain yield and agronomic performance with the check variety. Five of the varietal-cross hybrids had significantly higher grain yield than the check variety, ranging from 37 to 46%, but had fewer days to anthesis and silking under WW condition (Table 3). Estimates of broad-sense heritability for grain yield and most of the agronomic traits were moderate to high under managed drought stress, but were relatively high for grain yield, days to anthesis and silking under well-watered condition (Table 3).



(a) 2018/2019 weather data of Ikenne



(b) 2019/2020 weather data of Ikenne

Figure 1. Monthly rainfall (RF), relative humidity (RH), solar radiation (SR), minimum, and maximum temperature (Tmin and Tmax) during the evaluation of maize genotypes in 2018/2019 and 2019/2020 at Ikenne, Nigeria.

Table 2. Mean squares from analysis of variance of grain yield and agronomic traits of maize synthetics, their selection cycles, varietal-cross hybrids and a check evaluated under managed drought stress and well-watered condition in 2018/2019 and 2019/2020 at Ikenne, Nigeria.

Source	DF	Grain yield (t/ha)	Days to anthesis (days)	Days to silking (days)	Anthesis-silking interval (days)	Plant height (cm)	Ear aspect (1–5)	Stress tolerance index
				Managed drought stress				
Year (Y)	1	51.40***	16.26***	16.59**	65.71***	1412.48	2.41***	9.87***
Rep (Y)	6	1.91***	4.33***	14.25***	4.90**	562.20	0.41**	0.24***
Block (Rep ×Y)	25	0.69***	1.30	4.10*	1.59	1396.06	0.18	0.08***
Genotype	15	0.88***	1.69	6.73***	2.12*	1337.60	0.15	0.09***
Genotype ×Y	15	0.55*	1.02	2.25	1.34	1396.20	0.08	0.07**
Error	65	0.26	0.95	2.05	1.25	1161.76	0.11	0.03
				Well-watered condition				
Year (Y)	1	162.18***	72.34***	85.64***	0.56*	34,081.58***	4.46***	
Rep (Y)	6	2.25**	0.75	0.56	0.10	237.26	1.42***	
Block (Rep ×Y)	25	0.51	0.91	0.85*	0.10	94.01	0.17	
Genotype	15	2.21***	2.14***	2.85***	0.12	256.67*	0.25*	
Genotype ×Y	15	0.52	0.99	1.28**	0.17	113.02	0.29*	
Error	65	0.65	0.56	0.51	0.14	118.42	0.13	

*, **, ***: Significant at 0.05, 0.01, and 0.001 probability levels, respectively

Heterosis for grain yield and agronomic traits under managed drought stress and well-watered condition

The varietal-cross hybrids differed in heterosis for grain yield and other agronomic traits, both in magnitude and direction under the different moisture regimes. Under MDS, three varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1, and PVASYNHGBC1/PVASYNHGAC2) exhibited significant positive mid-parent heterosis (MPH), whereas two varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC1 and PVASYNHGBC1/PVASYNHGAC2) manifested significant positive better-parent heterosis (BPH) (Table 4). On the other hand, under well-watered condition, five varietal- cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1, PVASYNHGBC2/PVASYNHGAC1, and PVASYNHGBC1/PVASYNHGAC2) expressed significant positive MPH. Two of these hybrids (PVASYNHGBC0/PVASYNHGAC0 and PVASYNHGBC2/PVASYNHGAC0) also had significant positive BPH (Table 4). It is noteworthy that two varietal-cross hybrids (PVASYNHGBC1/PVASYNHGAC0 and PVASYNHGBC0/PVASYNHGAC2) under MDS and varietal-cross hybrid PVASYNHGBC1/PVASYNHGAC1 under WW conditions consistently expressed negative MPH and BPH for grain yield. They also had undesirable positive MPH for days to silking in the respective water regimes (Figure 2a). Under MDS, varietal-crosshybrids that had significant positive MPH for grain yield also had desirable negative MPH for ASI (Figure 2b). However, varietal-cross hybrids, except PVASYNHGBC1/PVASYNHGAC2,

Table 3. Mean performance and stress tolerance index of provitamin A maize synthetics, their selection cycles and varietal-cross hybrids evaluated under managed drought stress and well-watered condition in 2018/2019 and 2019/2020 at Ikenne, Nigeria.

	Managed drought stress							Well-watered condition					
	Grain yield (t/ha)	Days to anthesis (days)	Days to silking (days)	Anthesis-silking interval (days)	Plant height (cm)	Ear aspect (1–5)	Stress tolerance index	Grain yield (t/ha)	Days to anthesis (days)	Days to silking (days)	Anthesis-silking interval (days)	Plant height (cm)	Ear aspect (1–5)
PVASYNHGAC0	1.6	56.0	60.1	4.1	145.1	3.1	0.40	3.5	55.4	57.5	2.1	154.9	2.9
PVASYNHGAC1	1.6	55.9	59.3	3.4	139.6	2.9	0.43	3.8	54.4	56.5	2.1	165.4	2.7
PVASYNHGAC2	1.6	55.6	58.4	2.8	150.8	2.8	0.41	3.4	54.8	56.8	2.0	172.3	2.6
PVASYN HGBC0	1.6	55.0	57.9	2.9	148.9	2.8	0.50	3.2	55.0	56.9	1.9	167.1	2.9
PVASYNHGBC1	1.4	56.0	59.5	3.5	129.4	3.0	0.38	4.1	55.9	58.1	2.3	157.6	2.6
PVASYNHGBC2	1.6	55.4	58.0	2.6	136.1	2.9	0.41	3.6	54.0	55.6	1.6	162.9	2.4
PVASYNHGBC0/ PVASYNHGAC0	2.2	55.1	57.6	2.5	113.6	2.8	0.62	4.8	53.9	56.0	2.1	174.0	2.3
PVASYNHGBC1/ PVASYNHGAC0	1.3	56.5	60.6	4.1	140.5	3.0	0.32	4.3	54.4	56.3	1.9	157.0	2.5
PVASYNHGBC2/ PVASYNHGAC0	2.1	55.3	57.9	2.6	157.6	2.9	0.55	4.9	54.4	56.1	1.8	171.0	2.3
PVASYNHGBC0/ PVASYNHGAC1	2.3	55.0	57.6	2.6	139.8	2.6	0.70	4.8	54.1	56.1	2.0	170.4	2.4
PVASYNHGBC1/ PVASYNHGAC1	1.7	56.0	59.1	3.1	151.3	2.9	0.43	3.8	55.5	57.5	2.0	158.0	2.8
PVASYNHGBC2/ PVASYNHGAC1	1.8	54.5	57.1	2.6	150.5	2.9	0.46	4.9	54.0	55.9	1.9	175.5	2.3
PVASYNHGBC0/ PVASYNHGAC2	1.4	55.5	58.6	3.1	130.9	3.0	0.35	3.5	54.9	56.8	1.9	167.6	2.7
PVASYNHGBC1/ PVASYNHGAC2	2.7	55.0	57.8	2.8	140.9	2.5	0.72	5.1	54.6	56.5	1.9	173.9	2.4

(*Continued*)

Table 3. (Continued).

	Managed drought stress							Well-watered condition					
	Grain yield (t/ha)	Days to anthesis (days)	Days to silking (days)	Anthesis-silking interval (days)	Plant height (cm)	Ear aspect (1–5)	Stress tolerance index	Grain yield (t/ha)	Days to anthesis (days)	Days to silking (days)	Anthesis-silking interval (days)	Plant height (cm)	Ear aspect (1–5)
PVASYNHGBC2/ PVASYNHGAC2	1.8	55.1	57.8	2.6	152.0	2.8	0.48	3.8	54.0	56.0	2.0	172.9	2.3
PVASYN13	2.4	55.0	57.8	2.8	161.8	2.6	0.63	3.5	55.0	56.9	1.9	164.8	2.6
Mean	1.8	55.4	58.4	3.0	143.0	2.9	0.49	4.1	54.6	56.6	2.0	166.6	2.6
†LSD (0.05)	0.5	1.0	1.4	1.1	34.0	0.3	0.17	0.8	0.7	0.7	0.4	10.9	0.4
‡CV (%)	28.2	1.8	2.5	37.2	23.8	11.7	34.2	19.9	1.4	1.3	19.1	6.5	14.4
Heritability	0.4	0.5	0.7	0.4	0.0	0.4	0.20	0.8	0.8	0.7	0.0	0.6	0.1

†LSD: Least significant difference.
‡CV: Coefficient of variation

Table 4. Mid (MPH) and better-parent heterosis (BPH) for grain yield of nine provitamin A maize hybrids evaluated under managed drought stress and well-watered conditions in 2018/2019 and 2019/2020 seasons at Ikenne, Nigeria.

	Managed drought stress		Well-watered condition	
Hybrids	MPH	BPH	MPH	BPH
PVASYNHGBC0/PVASYNHGAC0	33.33*	32.52	42.94**	37.97*
PVASYNHGBC1/PVASYNHGAC0	−16.45	−21.12	14.13	4.85
PVASYNHGBC2/PVASYNHGAC0	30.86	30.06	39.94**	36.84*
PVASYNHGBC0/PVASYNHGAC1	43.13*	40.49*	37.07*	27.20
PVASYNHGBC1/PVASYNHGAC1	12.67	7.64	−2.67	−7.04
PVASYNHGBC2/PVASYNHGAC1	11.25	9.20	32.88*	30.40
PVASYNHGBC0/PVASYNHGAC2	−13.93	−14.72	4.96	1.45
PVASYNHGBC1/PVASYNHGAC2	74.92***	65.63**	34.92*	23.79
PVASYNHGBC2/PVASYNHGAC2	11.46	10.43	8.94	6.37
†SED (0.05)	0.30	0.34	0.50	0.58

*, **, ***: Significant at 0.05, 0.01 and 0.001 probability levels, respectively.
†SED: Standard error of difference.

had higher negative MPH for ear aspect score under WW condition than under MDS (Figure 2(a-c)).

Pearson's correlation coefficients between grain yield and agronomic traits under managed drought stress and well-watered condition

The relationships between grain yield and the flowering traits under both water regimes were negative but significant only under MDS (Table 5). However, under both water regimes, the correlation of grain yield with ear aspect was significant and comparable. The association between grain yield and STI was significant and positive. All the agronomic traits, except plant height, were significantly correlated with each other under MDS. On the contrary, ASI had no significant relationship with any trait under well-watered condition, except days to silking.

Discussion

Global fluctuations in climatic and weather factors call for the development of climate-resilient crop varieties. Efforts to combat the challenges caused by vitamin A deficiency in SSA by developing maize varieties with enhanced provitamin A content will be defeated if the varieties are highly susceptible to water deficits. Therefore, the evaluation of maize genotypes under differing stress conditions would facilitate the selection of lines that are adapted to a wide range of environments (Badu-Apraku et al. 2019). In the present study, the effects of managed drought stress on grain yield and agronomic performance of two provitamin A-enriched maize synthetics, their selection cycles and varietal-cross hybrids were investigated.

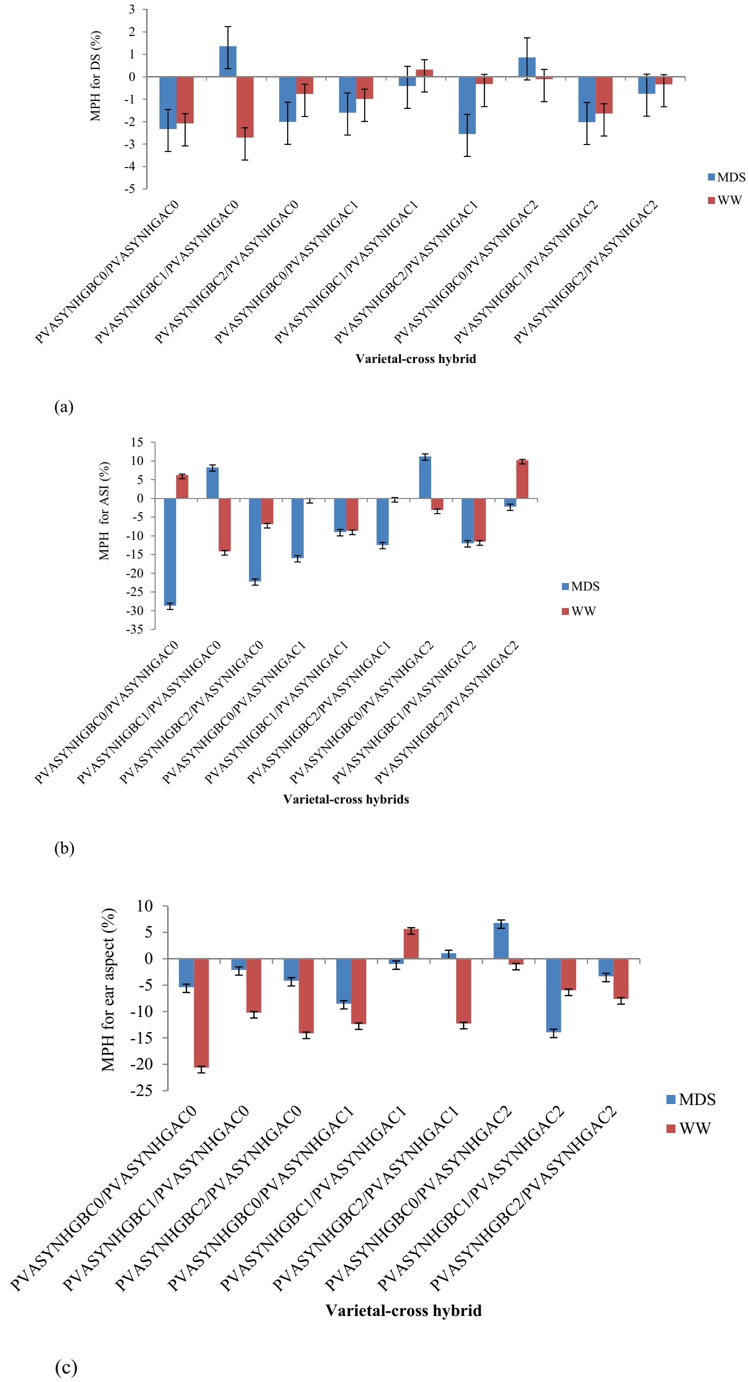


Figure 2. Mid-parent heterosis (MPH) for (a) days to silking, (b) anthesis-silking interval, and (c) ear aspect score of nine varietal-cross hybrids of provitamin A maize evaluated under managed drought stress (MDS) and well-watered (WW) conditions in 2018/2019 and 2019/2020 seasons at Ikenne, Nigeria.

Table 5. Pearson's correlation coefficients of grain yield and agronomic traits of provitamin A maize synthetics, their selection cycles, varietal-cross hybrids and a check evaluated under managed drought stress (top diagonal) and well-watered condition (bottom diagonal) in 2018/2019 and 2019/2020 dry seasons at Ikenne, Nigeria.

	Grain yield	Days to anthesis	Days to silking	Anthesis-silking interval	Plant height	Ear aspect	Stress tolerance index
Grain yield		−0.64**	−0.65**	−0.59*	0.17	−0.84***	0.96***
Days to anthesis	−0.44		0.96***	0.83***	−0.18	0.62*	−0.67***
Days to silking	−0.40	0.98***		0.96***	−0.14	0.67***	−0.67***
Anthesis-silking interval	−0.05	0.40	0.59*		−0.10	0.67***	−0.60**
Plant height	0.46	−0.65**	−0.63**	−0.21		−0.18	0.06
Ear aspect	−0.71***	0.76***	0.75***	0.31	−0.68***		−0.86***
Stress tolerance index	-	-	-	-	-	-	

*, **, ***: Significantly different from zero at 0.05, 0.01 and 0.001 probability levels, respectively, N = 16

The significant differences observed for grain yield, days to silking, ASI and STI among the provitamin A maize genotypes under MDS, are indications of the possibility of improving them for drought tolerance, as genetic variation is the basis for genetic advance in breeding programs (Pixley et al. 2013). In addition, the significant year effect for grain yield and all or most agronomic traits in the two water conditions indicated that the seasons differed, possibly because of variations in climatic conditions during field evaluation. Under MDS, the presence of significant genotype × year effect for grain yield suggested differential responses of the genotypes in each year of evaluation. It also implied that a single-year evaluation for yield would not be sufficient. On the other hand, the lack of genotype × year interaction for all the agronomic traits measured under MDS indicated that genotype performance with respect to these traits was stable in the two seasons of evaluation.

The effect of water regimes differed significantly for grain yield and all agronomic traits measured, which signified that the two water regimes elicited varying responses among the genotypes for the various traits. Timing, intensity, and uniformity of MDS are reported to be the key factors determining the effect of drought stress on grain yield and agronomic performance of maize (Bänziger et al. 2000; Zaidi 2019). The 56% reduction in yield attributable to drought stress in the present study indicated that the imposed drought stress targeted at flowering and grain filling stages was severe enough to discriminate among the genotypes. Previous studies showed that in maize, drought stress coinciding with flowering resulted in 17% to 60% yield losses (Edmeades et al. 1999; Aslam, Maqbool, and Cengiz 2015), whereas drought stress at flowering and grain-filling stages caused yield losses of about 40% to 90% (Menkir and Akintunde 2001; Meseka, Menkir, and Ajala 2011). Furthermore, the activation of moisture stress-adaptive mechanisms is reported to occur when the imposed stress has the potential to reduce yield by 30–50% (Edmeades et al. 2004). The yield loss recorded in this study was similar to the results reported among tolerant and resistant tropical maize inbred lines and hybrids (Meseka, Menkir, and Ajala 2011; Adebayo and Menkir 2014; Kumar et al. 2016; Rezende et al. 2020), but lower than the 78 and 79% yield losses reported among provitamin A maize hybrids (Manjeru 2017; Ortiz-Covarrubias et al. 2019).This suggested that some of the provitamin A-enriched maize genotypes included in this study exhibited improved tolerance to drought stress.

The parental synthetics and varietal-cross hybrids, which had ASI of more than three days, had significantly lower grain yields, compared to those with shorter ASI, suggesting that drought stress caused delayed silking, resulting in pollen asynchronization, and subsequent kernel abortion (Bänziger et al. 2000; Edmeades et al. 2000). Previous studies (Bänziger et al. 2000; Araus, Serret, and Edmeades 2012) have shown that ASI longer than three days is likely to result in silk senescence, abortion following pollination, barrenness, few grains per ear, and general yield loss. In this study, the significant correlation of days to anthesis and silking and ASI with grain yield under drought stress compared to the nonsignificant effect under well-water condition is indicative of the significant effect of drought stress at flowering and grain filling stages on grain yield reduction in the provitamin A maize genotypes. Anthesis-silking interval is a universally accepted indicator of the level of drought stress, and a good predictor of grain yield and barrenness under stress (Edmeades et al. 2000). Therefore, selection for reduced ASI and earliness can be an indirect selection criterion for drought tolerance and adaptation (Bänziger et al. 2000).

The significantly lower grain yield of the parental synthetics than the check variety as well as their low to moderate STI indicates that the parental synthetics and their selection cycles, except PVASYNHGBC0, did not exhibit high levels of tolerance to drought stress as compared to the drought-tolerant check variety. This could possibly be because the parental synthetics had not been previously selected for drought tolerance. However, most of the varietal-cross hybrids had desirable grain yield under drought stress, suggesting that recurrent selection could be effective in improving the parental synthetics for tolerance to drought. Recurrent selection of two to ten cycles for drought tolerance in several diverse tropical maize populations has been reported to increase grain yield by about 100 kg /ha/cycle and reduce ASI by 0.6 days/ year (Edmeades et al. 2000).

The comparable performance of the varietal-cross hybrids PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1, and PVASYNHGBC1/ PVASYNHGAC2 with the check variety under MDS and their concomitant significantly higher grain yield than the check variety under well-watered condition highlight the hybrids' tolerance to water stress. In addition, the moderate to high STI exhibited by the four varietal-cross hybrids accentuated their tolerance to drought stress. Similar STI values were reported by Oyekale et al. (2008) (STI = 0.62) and Kumar et al. (2016) (STI = 0.64). Some of the provitamin A-enriched varietal-cross hybrids in this study had desirable drought tolerance level that could be harnessed in breeding programs targeted at combating vitamin A deficiency in a wide range of environments prone to drought stress.

The different magnitude of heterosis for grain yield and agronomic traits among the varietal-cross hybrids under managed drought stress and well-watered condition highlighted the differential responses of the parents and varietal-cross hybrids under the two water regimes. The significant MPH of PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1, and PVASYNHGBC1/PVASYNHGAC2 for grain yield under the two water conditions indicated that these varietal-cross hybrids were well adapted to the two water conditions and could be used as sources of inbred lines to optimize heterosis under multiple water deficit environments. In addition, the varietal-crosshybrid PVASYNHGBC2/PVASYNHGAC0, which had relatively high MPH and BPH (> 30%) under the two water regimes, can be used as a commercial varietal-hybrid at an affordable cost for small-scale farmers. Several studies have reported that heterosis is often higher under MDS, especially under severe drought stress than under the corresponding WW conditions among inbred-derived maize hybrids (Betran et al. 2003; Makumbi et al. 2011; Naggar et al. 2016). This is because the differences in grain yield between hybrids and inbred lines increased with the intensity of drought stress, since inbred lines are more sensitive to environmental variations (Betran et al. 2003; Naggar et al. 2016). However, similar pattern was not observed for MPH and BPH for all the varietal-cross hybrids, probably because they were derived from synthetics, which are generally known to be more tolerant and adapted to drought stress than inbred lines (Kutka 2011). The degree of heterosis depends on the relative performance of parents and the corresponding hybrids, and is differentially affected by the environmental conditions under which they are evaluated (Betran et al. 2003; Munaro et al. 2011; Li et al. 2018). The magnitude of the MPH for grain yield manifested by the five varietal-cross hybrids under well-watered condition was comparable to those previously reported by Iseghohi et al. (2020) among the hybrids evaluated under rain-fed condition across eight different environments in Nigeria.

Under MDS, the negative heterosis for days to silking and ASI of most of the varietal-cross hybrids indicated early flowering and silking of the hybrids in comparison to their parents. This is desirable for breeding drought-tolerant maize genotypes as early flowering is reported to be one of the adaptive mechanisms of maize in escaping the effects of drought stress targeted at flowering stage (Badu-Apraku et al. 2011b). The varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1, and PVASYNHGBC1/PVASYNHGAC2), which had significant MPH for grain yield under MDS, also had desirable MPH for days to silking and ASI, suggesting that they could be deployed in maize breeding programs to optimize heterosis for drought tolerance as well as to combat vitamin-A deficiency in SSA.

Conclusions

Managed drought stress targeted at flowering and grain-filling stages of maize synthetics, their selection cycles and varietal-cross hybrids resulted in a 56% reduction in grain yield. Under MDS, three varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, PVASYNHGBC0/ PVASYNHGAC1) had similar grain yields and tolerance indices as the drought-tolerant check, whereas one varietal-cross hybrids (PVASYNHGBC1/PVASYNHGAC2) produced 12.5% more grain yield than the check. In addition, these hybrids had grain yields that were 37 to 46% higher than the check variety under well-watered condition. Three of the varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC1 and PVASYNHGBC1/ PVASYNHGAC2) had significant mid-parent heterosis for grain yield under managed drought stress and well-watered conditions, whereas PVASYNHGBC2/PVASYNHGAC0 had relatively high and appreciable levels of heterosis for grain yield under the two water regimes. These four varietal-cross hybrids were identified as potential candidates that could be used in breeding programs to develop high-yielding, drought-tolerant provitamin A-enriched hybrids to combat vitamin A deficiency in environments prone to drought stress in SSA.

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