Quantification of drought tolerance in Ethiopian common bean varieties

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ABSTRACT

Understanding the level of drought tolerance of the varieties available in each country is of paramount importance for breeding common bean for drought adaptation. The goal of this study was to evaluate 25 common bean genotypes of which 24 were released/recommended varieties for production by farmers and one was a drought tolerant check. The genotypes were planted at two sites in Ethiopia, Hawasssa and Amaro, using variable sowing dates, one that was early to avoid drought and one that was late to expose the crop to drought. The experiments were repeated over two years in Hawassa and one year in Amaro. This resulted in treatments with high and low total seasonal rainfall and six environments for analysis. The impact of drought stress on the trait expression of the varieties was not uniform across traits assessed and varieties tested. The effect of drought on photosynthate translocation and partitioning traits was much greater than on yield component traits in the varieties studied. This indicating less breeding efforts has been made in improving the varieties ability to mobilize photosynthate to the developing grain as compared to the yield component traits. Drought tolerant varieties like Hawassa Dume maintained better photosynthate translocation and partitioning than the drought sensitive varieties like Brown Speckled bean. Hawassa Dume also showed better yield stability and performed well under both drought stress and nonstress conditions. Our results indicate the relevance of high levels of photosynthate translocation and partitioning as an effective selection objective for improving drought tolerance in common bean. The information generated on the drought tolerance of the available varieties should help in the design of a breeding strategy that incorporates adaptation traits with commercial characteristics preferred by common bean farmers for varieties to be grown in diverse environments.

1. INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is the most important food legume in Ethiopia. While traditionally a food security crop throughout the country, its importance as a cash crop is gaining momentum in recent years through the sale of small white beans. These export-oriented beans have evolved into an important source of foreign currency for the country and income for smallholder farmers [1]. Common bean not only provides vital nutrients such as proteins, vitamins and minerals to the diets of the resource poor [2] but in Ethiopia is also important in providing fodder for feeding livestock and contributes to soil fertility improvement through atmospheric nitrogen fixation during the cropping season [3]. Thus as a legume, common beans add diversity to production systems on resource poor farmers' fields and contributes to the stability of farming systems in Ethiopia.

Common bean production in Ethiopia mainly occurs on smallholder farms prone to either intermittent or ter-

minal drought risk [4]. In common bean, drought stress is more serious than other abiotic stresses making it a key challenge to the livelihood of vulnerable environments. Drought is estimated to cause significant harvest losses across sub-Saharan Africa, with an estimated yield reduction of 300,000 MT annually [5].

Many studies have shown that drought has a drastic effect on common bean crop performance. These include tissue specific plus whole plant effects [6-10]. Drought stress can cause flower abortion, pod drop, poor rates of photosynthesis and reduced seed filling [11]. Drought also affects overall biomass and seed yield, photosynthate translocation and partitioning, number of pods and seeds, seed weight, days to maturity and root length and mass [9,12-14]. In addition, drought reduces P uptake as well as N concentration and fixation [15,16].

In most parts of the world, drought episodes are becoming or are predicted to become more frequent in occurrence and often more intense in magnitude [10]. Complete or partial crop failure due to drought continues to be a common phenomenon [17,18]. Moreover, several places where drought is already a problem in Africa such as in Ethiopia and southern Africa will suffer from warmer and successively-drier weather linked with climate change over the next few decades [19]. Thus, drought stress is the most important limitation facing crops now and in the future.

Improving crop performance in harsh environments where drought is limiting remains one of the most important and challenging issues for breeders, farmers, researchers, development agents and policy makers. In some regions the challenge will be even more intimidating with an increasing scarcity of rainfall and water in the future. This will make improving adaptation to drought stress a major objective of many crop breeding efforts. Drought tolerance once packaged in the form of seed in a variety can easily be used by many farmers for battling against drought effects in common bean production.

Making significant genetic gain for adaptation to drought stress in breeding requires a better understanding of the level of drought tolerance in the current varieties used in each country. In this regard, our study will focus on the many genotypes of common bean developed for Ethiopia where regional preference differences demands a range in commercial seed classes. The levels of drought tolerance of these released/recommended genotypes for production by Ethiopian farmers have not been well documented. Indeed only a few studies have tested breeding lines for drought stress and farmers perception of their drought tolerance [9,20,21]. The overall objective of this study was to assess the level of drought tolerance in Ethiopian common bean released/recommended varieties for production by farmers.

2. MATERIAL AND METHODS

2.1. Experimental Sites and Drought Trial

Drought phenotyping experiments were conducted at two field sites in Ethiopia in the 2008 and 2009 cropping seasons: namely, Hawassa and Amaro research farms that belong to the South Agricultural Research Institute (SARI).

The Hawassa site is located at 7˚03'N latitude, 38˚30'E longitude at an elevation of 1700 m above sea level. The soil at this site is a well-drained sandy-loam (Flovisol, FAO classification) with pH 7.0. The yearly average maximum and minimum temperatures of the site are 26.9˚C and 12.4˚C, respectively, and annual rainfall is 959 mm on average. Rainfall at this site is bimodal with total seasonal amount of 296 mm and 444 mm during the short "*Belg*" rainy season (March-May) and the long "*Meher*" rainy season (July-October), respectively.

The Amaro site is located at 5˚50'N latitude, 37˚55'E longitude at an elevation of 1426 m above sea level. The soil at this site is a well-drained silt-clay-loam (Eurtic nitosols, FAO classification) with pH 6.5. The yearly average maximum and minimum temperatures is 27.6˚C and 15.2˚C, respectively, and annual rainfall is 927 mm (412 mm and 294 mm during the "*Belg*" and "*Meher*" growing seasons, respectively).

The trials were planted in the "*Meher*" (from July-October) season at Hawassa across two years (2008 and 2009) and in the "*Belg*" (March-June) season at Amaro in 2009 using two different sowing dates in each season: one that was early to avoid drought and one that was late to expose the crop to terminal drought. The result was treatments with high and low total seasonal rainfall during the growing season. Total rainfall was recorded on a daily basis with a rain catchment system. Drought-stressed and nonstressed conditions were applied as separate experiments in each trial site which created six environments for analysis.

2.2. Plant Material and Treatment Design

Twenty four released/recommended varieties of common bean for Ethiopia of both large-seeded and small-seeded types as well as one small red-seeded drought tolerance check (SER108) obtained from the International Center for Tropical Agriculture (CIAT) were used for this study making a total of 25 genotypes in the experiment. The common bean material represented both Andean and Mesoamerican genepools with the list of the genotypes, genepool identity and their date of release presented in **Table 1**. An Andean drought-tolerant check genotype was not available at the time of the experiments but a recommended CIAT Andean line (AFR-702) was part of the list of recommended and released varieties

Table 1. List of materials evaluated for the trial of Ethiopian varieties under drought and nonstress conditions in Hawassa and Amaro in southern Ethiopia over two years.

Variety code	Name of varieties	Gene pool	Status	Year of release
V1	Denkenesh	Mesoamerican	Released variety	2007
V2	Dimitu	Mesoamerican	Released variety	2003
V3	Melkadima	Mesoamerican	Released variety	2006
V 4	Zebra	Mesoamerican	Released variety	1999
V5	Gofta	Mesoamerican	Released variety	1997
V6	Atndaba	Mesoamerican	Released variety	1997
V7	Awash Melka	Mesoamerican	Released variety	1999
V8	Naser	Mesoamerican	Released variety	2003
V9	Mex 142	Mesoamerican	Released variety	1973
V10	Argene	Mesoamerican	Released variety	2005
V11	Chore	Mesoamerican	Released variety	2006
V12	Red Wolayta	Mesoamerican	Released variety	1974
V13	Ayenew	Mesoamerican	Released variety	1997
V14	Cranskope	Andean	Registered variety	2007
V15	Red Kidney	Andean	Registered variety	2007
V16	Awash-1	Mesoamerican	Released variety	1990
V17	Omo-95	Mesoamerican	Released variety	2003
V18	Ibado	Andean	Released variety	2003
V19	Goberasha	Andean	Released variety	1999
V20	Tabor	Mesoamerican	Released variety	1999
V21	Hawassa Dume	Mesoamerican	Released variety	2008
V22	SER-108	Mesoamerican	Drought resistant check	#
V23	Brown Speckled	Andean	Unknown	NK
V24	AFR-702	Andean	Recommended variety	2004
V25	RAB-585	Mesoamerican	Recommended variety	2004

Note: NK= unknown, # = drought tolerance check obtained from CIAT.

along with the CIAT Mesoamerican line (RAB-585). In all the experiments, a 5×5 triple lattice treatment design was used. The plot sizes were 4 rows of 2 m length by 0.4 m width. In all the experiments, DAP (diammonium phos- phate) fertilizer was applied at time of sowing at rate of 100 kg·ha^{-1} to raise a good crop. The experimental plots were hand weeded making the crop free of weed when- ever necessary.

2.3. Plant Trait Measurements

For quantifying the physiological differences in drought tolerance, a number of photosynthate translocation and partitioning (PTP) traits were measured through destructive sampling at mid-pod fill and at harvest maturity using the procedure specified by reference [9]. For the plant traits at mid-pod filling, a row length of 0.5 m (0.2 m^2 area) for each plot was selected and the plants were cut to the soil surface above the ground and put in a paper bag for processing in the laboratory. Plants were separated into leaves (without petioles), stems and the remaining (pods and reproductive structures) plant parts. The plant parts were put in separate paper bags and oven dried at 80°C for 2 days. After drying of the samples, dry weight of each sample was measured to determine total dry matter production and dry matter distribution in dif

ferent plant parts (leaf biomass, stem biomass and pod biomass).

At harvest, plants within 0.5 m long row (0.2 m^2 area) were cut to the soil surface and oven dried at 80°C for 2 days. The oven dried samples were then separated into plant parts: stem, pod wall and seeds, and dry weight measurements were recorded. Physiological traits including, leaf stem ratio (LSR) at mid-pod fill, pod partitioning index (PPI), pod harvest index (PHI), stem biomass reduction (SBR) and harvest index (HI) at harvest maturity determined were as described in Reference [9]. These data were collected only at Hawassa in 2009 but not at Amaro 2008 and Hawassa 2008 due to labor shortage except for PHI which was measured in all experiments.

LSR was calculated as the ratio of dry matter distribution into leaf biomass and stem biomass at the mid-pod fill stage. PPI was determined as the ratio of dry weight of pods at harvest over dry weight of total biomass at the mid-pod fill stage multiplied by 100. Similarly, PHI was calculated as the ratio of dry weight of seed over dry weight of pod at harvest multiplied by 100. SBR was calculated as stem biomass at the mid-pod fill stage minus stem biomass dry weight at harvest over stem biomass dry weight at mid-pod fill multiplied by 100. HI was determined as the ratio of seed dry weight at harvest over dry weight of total biomass at the mid-pod fill stage multiplied by 100.

In addition, phenological traits like days to flowering (number of days from sowing to 50% plants at least one open flower in a plot) and days to maturity (number of days from sowing to at least 90% of plants reach physiological maturity in a plot) were recorded along with pods per plant, seeds per pod, grain yield (in $kg \cdot ha^{-1}$) and 100 seed weight in all experiments.

2.4. Phenotypic Data Analysis

Mixed model analyses of variance (ANOVAs) were carried out using the program Genstat v. 12.1 [22], first for single environments and then combined across environments to determine genotype × environment interaction (G×E) following reference [23]. Both types of ANOVAs used a Residual Maximum Likelihood (REML) procedure. The models use were

$$Y_{iklm} = \mu + g_i + m_k + r_l + b_m + \varepsilon_{iklm} \quad (1)$$

where Y is mean performance of a certain genotype, μ the overall mean, g_i the effect of genotype i, m_k the effect of genepool k, r_l the effect of replicate l, b_m the effect of block m and ε_{iklm} the residual associated with single plot for single environment analysis and

$$Y_{ijklm} = \mu + g_i + e_j + ge_{ij} + m_k + r_l + b(r)_{m(l)} + \varepsilon_{ijklm} \quad (2)$$

where Y is mean performance of certain genotype, μ the

overall mean, g_i the effect of genotype i, m_k the effect of genepool k, e_j the effect of environment j, ge_{ij} the interaction between genotype i and environment j, r_l the effect of replicate l, $b(r)_{m(l)}$ the effect of block m nested within replicate l and ε_{ijklm} the residual associated with single plot for combined environment analysis.

In the single environment analysis, block effects were added to the model as a random effect when significant for a trait whereas replication was considered as a fixed effect. This was performed to remove the spatial variation within the trial field. Genotypes were considered as a fixed effect to get un-shrunken means (best linear unbiased estimates = BLUEs).

For the combined environment (G×E) analysis, blocks within replication, and environments were considered as random effects whereas replication and genotypes were modeled as fixed effects. For estimation of variance components in the combined environment or G×E model, genotypes were set as random. Variance components and broad-sense heritability (h^2_{BS}) estimates were calculated for global (combined stress/nonstress environments) and set of drought stressed and nonstressed environments independently for making comparison. The broad sense heritability was estimated across e environments and r replicates [24]

$$h^2_{BS} = \frac{\sigma^2 g}{\sigma^2 g + \dfrac{\sigma^2 ge}{e} + \dfrac{\sigma^2 \varepsilon}{er}} \quad (3)$$

where $\sigma^2 g$, $\sigma^2 ge$, $\sigma^2 \varepsilon$ are genetic, genotype × environment, and residual variance component respectively.

Phenotypic correlations between grain yield and other variables were assessed using Pearson's correlation coefficients as *per* a procedure implemented in the Genstat v. 12.1 programs. The significance of correlations was tested with t-tests based on the formula:

$$t = r\sqrt{\frac{n-2}{1-r^2}} \quad (4)$$

where the degrees of freedom was equal to $n - 2$.

To quantify the severity of drought stress on grain yield, a drought intensity index (DII) for yield was calculated as DII = 1 − G$\bar{Y}$p/G$\bar{Y}$i, where G$\bar{Y}$p and G$\bar{Y}$i were the mean experimental yield values of all varieties grown under drought stress and nonstress, respectively [25]. Drought intensity index was also calculated for other traits measured in the trial adopting the formula for grain yield, one minus mean trait value under stress over nonstress for all the varieties and for the varieties in Andean and Mesoamerican genepool groups for comparison of drought tolerance level between varieties within genepool groups.

Other drought indices for grain yield, such as the stress tolerance index (STI = (GYi) × (GYp)/(G$\bar{Y}$i)^2),

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geometric mean productivity (GMP = [(GYi) × (GYp)]$^{0.5}$) index, the mean productivity (MP = (GYi + GPp)/2) index and the stress tolerance (TOL = (GYi − GYp)) index were calculated as *per* procedures documented in reference [26,27]. In all cases GYi and GYp were the grain yields of varieties under nonstress and drought stress conditions, respectively. These indices were subjected to mixed model analysis to estimate variance components and means as model specified in Equation (2).

For assessing yield stability of the varieties, a genotype × environment (G × E) table was prepared using the BLUE means from the single environment analysis. Stability for grain yield and other traits (days to flowering, days to maturity, 100 seed weight, pod harvest index, pods per plant and seeds per pod) for which data were available for all the six test environments were computed using a cultivar superiority measure (Pi) of reference [28] as *per* procedures implement in Genstat v.12.1. Cultivar superiority (Pi) was estimated as

$$Pi = \sum_{j=1}^{\theta} (Xij - Mj)^2 \Big/ (2e) \qquad (5)$$

where e is the number of environment, Xij trait value of ith variety grown in the jth environment, Mj maximum

trait value (response) of certain variety among all varieties in jth environment. For days to flowering and days to maturity, Pi was estimated using Mj as minimum trait value of certain variety among all varieties in jth environment. In addition, a varietal evaluation was made based on both average grain yield and stability using the GGE biplot procedure of reference [29] in Genstat software.

3. RESULTS

3.1. Level of Drought Stress and Effects on Mean Trait Values

Weather conditions (rainfall amounts as well as maximum and minimum temperatures) during the crop growing period in each trial environment are presented in **Figure 1**. The average maximum and minimum temperatures for the Hawassa site 2008 were 24.7°C and 13.0°C in early planting and 25.5°C and 12.9°C in late planting; and 27.8°C and 12.2°C in nonstress (early planting) and 28.6°C and 11.5°C in terminal drought stress (late planting) in 2009. Rainfall events were sporadic (**Figure 1(a)**, **1(b)**, **1(c)**, **1(d)**).
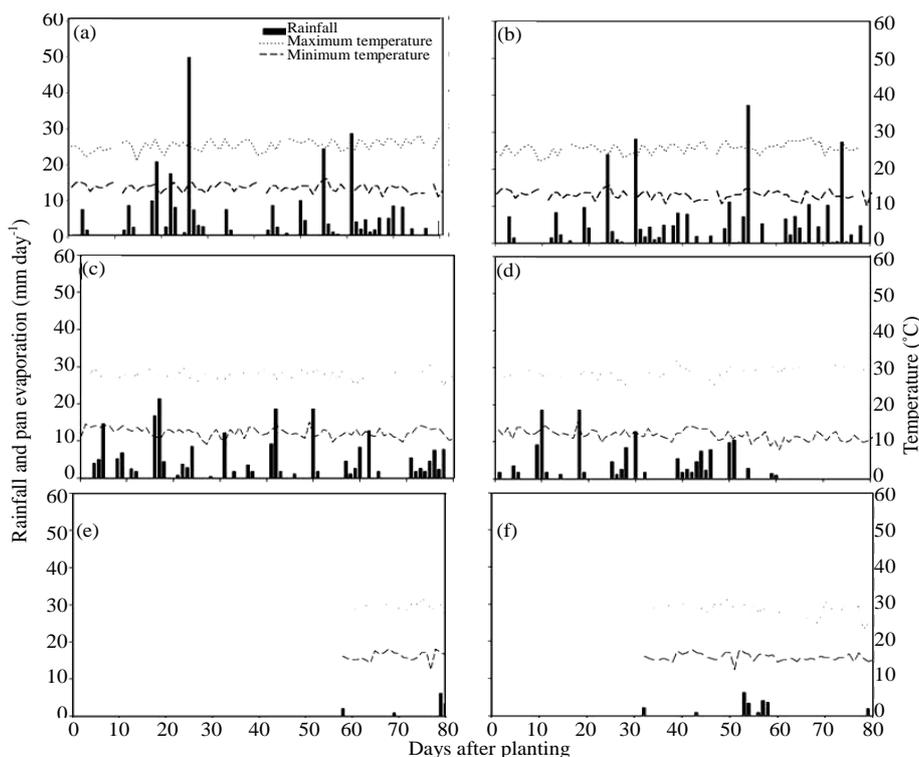

Figure 1. Rainfall distribution (bars), maximum and minimum temperatures (broken lines) during the crop growth period at different trial locations. (a) Hawassa early sowing 2008; (b) Hawassa late sowing 2008; (c) Hawassa early sowing 2009; (d) Hawassa late sowing 2009; (e) Amaro early sowing 2009; and (f) Amaro late sowing 2009, with the same x-axis in days after planting shown bottom of the subfigures for the two sites but with different y-axis to the right and left of the graphs. Subfigures (a), (d) and (f) were considered as drought stress (DS) environments and subfigures (b), (c) and (e) were taken as nonstress (NS) environments.

The weather data of Amaro were not available for the full crop growing cycle. However, on the basis of the end of the season, the average maximum and minimum temperatures, respectively, were 20.2°C and 16.0°C in the nonstress trial (early planting) from 58 to 80 days after planting and 26.9°C and 15.4°C in the terminal drought-stress trial (late planting) from 32 to 80 days after planting. Again, rainfall was sporadic during the period of evaluation (Figures 1(e) and (f)).

The total rainfalls for the Hawassa early and late planting dates were 279 mm and 282 mm in 2008 cropping season and 235 mm and 149 mm in 2009 cropping season, respectively. The weather parameters during the crop growth period indicated that the crop suffered terminal drought stress in late planting trials at the Hawassa and Amaro sites in 2009 and intermittent drought stress mainly at flowering at the Hawassa site in the early but not the late planting in the 2008 cropping season. As a result, the Hawassa 2008 early planting was considered a drought-stressed environment and the Hawassa 2008 late planting trial which did not experience stress was considered a nonstress environment for the analysis in this paper.

Drought stress caused remarkable reduction in mean performance of the varieties for the traits studied except for leaf-stem dry weight ratio and stem biomass reduction (Table 2). Mean grain yield over the three environments was 55% lower in the drought stress condition than in the nonstress condition based on the drought intensity index calculated from the mean yield of all varieties under stress *versus* nonstress environments. Average grain yields of all varieties including the drought tolerant check were 2950, 2514 and 1123 kg·ha^{-1} in the nonstress environments in Hawassa 2008, Hawassa 2009 and Amaro 2009, respectively. Meanwhile in the drought-stress environment of the same sites the yields were 2088, 508 and 375 kg·ha^{-1}, respectively. As a result, the mean grain yield showed 29.2%, 79.8%, and 66.6% reductions due to drought stress in the Hawassa 2008, Hawassa 2009, and Amaro 2009 trials, respectively. This showed that drought stress for grain yield was moderate in Hawassa 2008 but severe in Hawassa 2009 and Amaro 2009 cropping season trials.

Drought stress caused the varieties to flower and mature relatively faster. Drought stress also caused poor pod-partitioning and harvest index as shown by the other indices and traits evaluated at harvest: mean reductions due to drought stress were 70% for the pod-partitioning

Table 2. The effect of drought stress on mean trait value of common bean varieties (all 25 varieties irrespective of genepool grouping, 6 varieties in Andean and 19 varieties in Meso-American genepool groups) evaluated at drought stress and nonstress environments in Hawassa and Amaro sites in southern Ethiopia over two years. Mean trait values for photosynthate translocation and partitioning traits: leaf-stem ratio, pod portioning index, stem biomass reduction and harvest index were specific to Hawassa 2009 trial whereas for the rest of the traits measurements were made for Hawassa in 2008 and 2009 and for Amaro in 2009.

| Traits | Mean values over environments[*] | | | | | | Drought intensity index | | |
| | NS | | | DS | | | | | |
	ALL	AND	MESO	ALL	AND	MESO	ALL	AND	MESO
DF	44.95	45.14	44.76	43.50	43.91	43.09	0.03	0.03	0.04
DM	87.57	87.33	87.79	85.54	85.47	85.61	0.02	0.02	0.02
LSR	1.31	1.28	1.34	1.30	1.00	1.60	0.01	0.22	−0.19
PPI	85.07	81.23	88.92	25.78	18.40	33.17	0.70	0.77	0.63
SBR	46.08	46.89	45.27	54.71	53.52	55.90	−0.19	−0.14	−0.23
PHI	72.57	72.04	73.10	68.89	68.10	69.68	0.05	0.05	0.05
HI	63.41	60.42	66.41	16.82	10.76	22.88	0.73	0.82	0.66
PPP	13.05	12.52	13.58	10.17	10.87	9.47	0.22	0.13	0.30
SPP	3.80	3.57	4.03	3.48	3.40	3.60	0.08	0.05	0.11
GYLD	2195.38	1786.70	2324.43	990.48	884.82	1023.85	0.55	0.50	0.56
HSW	28.50	30.97	26.03	25.39	25.39	24.73	0.11	0.18	0.05

DF = Days to 50% flowering; DM = Days to 90% maturity; LSR = Leaf-stem ratio (dry weight); PPI = Pod partitioning index (%); SBR = Stem biomass reduction (%); PHI = Pod harvest index (%); HI = Harvest index (%); PPP = Pods per plant (number); SPP = Seeds per pod (number); GYLD = Grain yield kg·ha^{-1}; HSW = 100 seed weight (gm); ALL = All test genotypes; AND = Andean genepool groups; MESO = Meso-Ammerican genepool groups; NS = nonstress environments; DS = Drought stressed environments; **Note**: [*]Mean values over environment were based on n = 3 for days to 50% flowering, days to 90% maturity, pod harvest index, pods per plant, seeds per pod, grain yield kg·ha^{-1} and 100 seed weight whereas for the rest traits n = 1; n is number of environment.

index, 5% for the pod harvest index, 75% for harvest index, 22% for the number of pods per plant, 8% for the number of seeds per pod and 11% for 100 seed weight. On the other hand, increased photosynthate mobilization from stem reserve was observed under drought stress environments compared to the nonstress environments. Under similar comparison, Andean varieties showed higher sensitivity to drought for expression of pod-partitioning index, harvest index and hundred seed weight whereas the Mesoamerican varieties were more sensitivity to drought in expression of pods per plant and seeds per pod (Table 2). In both genepool groups, the effect of drought on photosynthate mobilization from pod wall to the grain was small indicating varieties with better ability to translocating photosynthate from pod wall to grain under nonstress condition may repeat the same efficiency under drought stress environments too.

The responses of individual varieties even though not similar under the observed two drought patterns, the overall reduction in yielding potential and other trait performances were observed. Under the intermittent drought in Hawassa 2008, the varieties expressed better yielding potential and performance for other traits compared to the terminal drought effect in both Hawassa and Amaro sites in 2009 cropping season (Data not shown).

Such differences in varietal performance under the two drought patterns and also under nonstress environments were assessed with stability analysis section later in the paper rather than presenting the results to drought patterns differently.

3.2. Variance Components, Heritability and Correlations of Grain Yield and Other Traits in the Environments

Table 3 presents probability values for testing genotypic effect, the variance components and heritability of different traits assessed in the 25 common bean varieties and their correlations with grain yield under drought stressed and nonstressed environments. Considerable variation for the expression of phenotypic values was observed for the majority of the traits among the varieties. The varietal difference for drought stress and nonstress environments combined (global) analysis was highly significant ($p < 0.001$) for expression of traits including days to 50% flowering, days to maturity, grain yield, hundred seed weight, pod harvest index, pods per plant, seeds per pod and mean performance. For parameters like leaf-stem ratio, stress tolerance index and geometric mean productivity, the varietal difference was significant at 5% probability. Nonsignificant differences were observed among varieties for expression of the traits; harvest index, pod partitioning index and stem biomass reduction within some individual sites. When independent

$G \times E$ analysis was conducted for the set of environments in drought stress and nonstress category, the varietal difference was significant for all traits measured under nonstress environments and except grain yield and leaf stem ratio under drought stress environments.

The $V_{G \times E}$ variance was greater than the genetic variance for the majority of traits measured and drought selection indices calculated in global as well as specific analysis for drought stress and nonstress environments independently. Higher $G \times E$ interaction was observed for grain yield ($kg \cdot ha^{-1}$), days to maturity, leaf-stem ratio, pod partitioning index, harvest index, mean productivity, geometric mean productivity and stress tolerance indices in global analysis. On the other hand, the genetic variance (V_G) was greater than $V_{G \times E}$ variance for days to 50% flowering, pods per plant, seeds per pod, 100 seed weight and stress tolerance index. For pods per plant under nonstress environments, the $V_{G \times E}$ variance was higher compared to genetic variance. For photosynthate partitioning traits like stem biomass reduction and pod harvest index, the V_G variance was almost equal to the $V_{G \times E}$ variance.

The broad-sense heritability values in global analysis ranged substantially for all the traits measured and indices calculated, being especially low for pod partitioning index (0.18) but much higher for 100 seed weight (0.96) followed by days to 50% flowering (0.94), stress tolerance index (0.88), pods per plant (0.80), and pod harvest index (0.75). The heritabilities were intermediate for grain yield (0.65), days to maturity (0.69), seeds per pod (0.61), and mean productivity (0.56). Relatively low heritabilities (0.24 - 0.44) were observed for leaf-stem ratio, stem biomass reduction, harvest index, geometric mean productivity and stress tolerance. The heritabilities were observed to be generally lower in drought stress environments compared to the nonstress environments for majority of the traits except pods per plant, pod partitioning index and harvest index.

The phenotypic Pearson's correlation values between traits and grain yield are shown in the last columns of Table 3 for both drought and nonstress environments. Positive and significant associations were observed between grain yield and days to 50% flowering, days to 90% maturity, seeds per pod, pod harvest index, stress tolerance index, mean productivity and geometric mean productivity over drought stress and nonstress environments.

Under drought-stress environments, the correlations with grain yield were positive and significant for yield component traits, pods per plant and for the photosynthate partitioning trait for harvest index. The pod-partitioning index had positive but nonsignificant correlation with grain yield under both drought stress and nonstress environments while the correlations with grain yield were negative and nonsignificant for leaf-stem ratio and

Table 3. Probability values for testing genotypic effect, estimates of variance components [genetic (σ_g^2), genotype × environment interaction (σ_{ge}^2) and phenotypic (σ_p^2)], broad-sense heritability (h_{BS}^2) global (all test environments stress and nonstress combined), drought stress and nonstress environments separate, and phenotypic correlations of traits and drought indices with grain yield of common bean varieties evaluated at drought stress and nonstress environments in Hawassa and Amaro in southern Ethiopia over two years.

Traits	Variance component											Heritability broad sense (h^2_{BS})			Correlation with grain yield kg·ha^{-1}	
	Global				DS				NS							
	p-values	σ_g^2	σ_{ge}^2	σ_p^2	P-values	σ_g^2	σ_{ge}^2	σ_p^2	P-values	σ_g^2	σ_{ge}^2	σ_p^2	Global	DS	NS	DS	NS
GYLD	0.001	53676	136009	82931	0.423	1889	102288	36812	0.005	103268	168473	161615	0.65	0.05	0.64	1	1
Phenology																	
DF	0.001	7.67	2.129	8.13	0.001	5.79	3.78	7.08	0.001	8.855	0.92	9.19	0.94	0.82	0.96	0.19[**]	0.38[***]
DM	0.001	2.32	4.501	3.34	0.001	1.59	4.91	3.30	0.037	1.789	5.08	3.54	0.69	0.48	0.51	0.81[***]	0.72[***]
Yield components																	
PPP	0.001	5.57	4.53	7.01	0.001	4.10	2.66	5.11	0.002	6.54	7.24	9.13	0.80	0.80	0.72	0.45[***]	0.05
SPP	0.001	0.39	0.17	0.63	0.005	0.30	0.18	0.38	0.001	0.53	0.13	0.58	0.61	0.80	0.91	0.53[***]	0.34[***]
HSW	0.001	50.77	4.99	52.62	0.001	32.19	4.13	33.82	0.001	72.89	2.62	73.99	0.96	0.95	0.99	0.07	−0.23
Physiological traits																	
LSR	0.05	0.03	0.07	0.09	0.402	0.19		0.96	0.001	0.0392		0.05	0.34	0.20	0.82	−0.04	−0.07
SBR	0.127	34.8	35.1	88.43	0.021	83.70		99.3	0.003	91.8		104.5	0.39	0.84	0.88	−0.20	−0.11
PPI	0.320	9.1	50.5	51.18	0.001	73.73		79.97	0.009	39.5		49.13	0.18	0.92	0.80	0.21	0.12
PHI	0.001	6.48	6.84	8.62	0.055	9.88	8.71	13.10	0.003	4.93	2.76	6.01	0.75	0.75	0.82	0.53[***]	0.50[***]
HI	0.251	6.97	22.83	28.56	0.001	46.69		51.00	0.04	13.85		20.55	0.24	0.92	0.67	0.23[*]	0.17
Drought indices																	
STI	0.049	0.09	0.03	0.11									0.88			0.84[***]	0.60[***]
MP	0.009	46106	91371	82959									0.56			0.87[***]	0.91[***]
GM	0.045	29972	99758	68402									0.44			0.95[***]	0.80[***]
TOL	0.128	38338	179160	122745.5									0.31			−0.32	0.58[***]

Note: For abbreviations of traits refer **Table 2** and abbreviations for drought indices are the following: STI = Stress tolerance index, GMP = Geometric mean productivity, MP = Mean productivity, TOL = Stress tolerance, correlations between yield and physiological parameter allude to where the parameters measured at Hawassa in 2009; [*], [**], [***] indicates significance at p < 0.05, p < 0.001 and p < 0.0001 level, respectively.

stem biomass reduction at both Hawassa and Amaro sites. The relationship between grain yield and 100 seed weight was positive and nonsignificant under drought stress and negative and nonsignificant under nonstress environments. Grain yield was correlated with stress tolerance index in drought-stress environments.

3.3. Varietal Performances under Drought Stress and Drought Selection Indices

Mean grain yield over environments and drought selection indices are presented in **Table 4**. Under drought stress conditions, the grain yield of 25 varieties ranged from 441 to 1384 kg·ha^{-1}. Among the varieties eva-

luated, Dimitu, Red Wolayta, Omo-95 and Hawassa Dume from the Mesoamerican genepool, and Ibado and AFR-702 from the Andean genepool expressed better adaptation to the drought stress conditions.

Among these better adapted drought stress tolerant varieties, Hawassa Dume was also responsive to well-watered condition. Brown Speckled and Cranskope were the most poorly adapted varieties both under nonstress and drought stressed conditions. Based on different drought selection indices, varieties like Hawassa Dume and Red Wolayta with high STI, MP and GMP values were better yielding under both regimes.

Conversely, the variety ranking with stress tolerance

Table 4. Mean grain yield and drought selection indices over six environments for 25 common bean varieties grown in nonstress and drought stress environments in Hawassa and Amaro in southern Ethiopia over two years.

Varieties	Mean grain yield kg·ha^{-1} over environments (n = 3)		Drought indices			
	Non-stress	Drought stress	STI	GM	MP	TOL
Denkenesh	2476.0	1050.5	0.57	1520	1765	1408
Dimitu	2012.4	1384.4	0.51	1553	1675	623
Melkadima	2202.0	1006.2	0.45	1409	1611	1224
Zebra	2791.4	1083.4	0.49	1590	1922	1723
Gofta	2024.8	787.9	0.29	1152	1382	1284
Atndaba	2360.0	1030.8	0.38	1405	1665	1365
Awash Melka	1872.8	970.7	0.30	1207	1413	876
Naser	2671.4	949.2	0.51	1560	1806	1709
Mex 142	1761.3	793.6	0.27	1101	1282	964
Argene	1878.6	847.0	0.36	1228	1374	1027
Chore	2218.7	952.8	0.42	1401	1592	1270
Red Wolayta	2429.7	1335.8	0.71	1771	1920	1091
Ayenew	2064.6	1045.3	0.39	1417	1565	1011
Cranskope	1412.7	558.5	0.13	832	991	833
Red Kidney	1598.1	1060.5	0.27	1156	1312	578
Awash-1	2602.9	1085.2	0.54	1583	1839	1571
Omo-95	2426.4	1269.7	0.53	1627	1842	1157
Ibado	2192.4	1169.1	0.45	1516	1691	1032
Goberasha	1882.4	974.0	0.32	1264	1446	926
Tabor	2080.9	826.4	0.34	1286	1479	1272
Hawassa Dume	3322.2	1186.1	0.77	1948	2253	2082
SER-108	2438.1	929.2	0.45	1451	1683	1454
Brown Speckled	1480.2	441.2	0.19	797	962	996
AFR-702	2154.4	1105.6	0.50	1488	1634	1071
RAB-585	2530.0	918.9	0.45	1478	1721	1580
ASED	392.3	125.1	0.158[*]	279.2[*]	274.5[**]	(415.1)

Note: ASED = Average Standard Error of Difference, [*] and [**] indicates probability level 5% and 1% respectively; Abbreviations for drought indices are the following: STI = Stress tolerance index, GMP = Geometric mean productivity, MP = Mean productivity, TOL = Stress tolerance.

index (TOL) was in reverse order from that of the other indices considered. Accordingly, Hawassa Dume which ranked first according to the STI, MP and GMP values ranked last with TOL values. Red Kidney was identified as the best in the degree of tolerance to drought with TOL values but it was not a high yielding variety under well-watered conditions.

Figures 2 and **3** present the relationship between grain yield and photosynthate translocation and partitioning (PTP) traits under drought stress and nonstress condi-

tions. The relationship between grain yield and pod harvest index showed that the variety Hawassa Dume was outstanding in mobilizing photosynthates to seed development both under drought stress and nonstress condition. Meanwhile, Red Wolayta and Brown Specked showed poor ability to partition photosynthetically assimilated carbon to seed as reflected by lower values of pod harvest index under both nonstress and drought stress conditions.

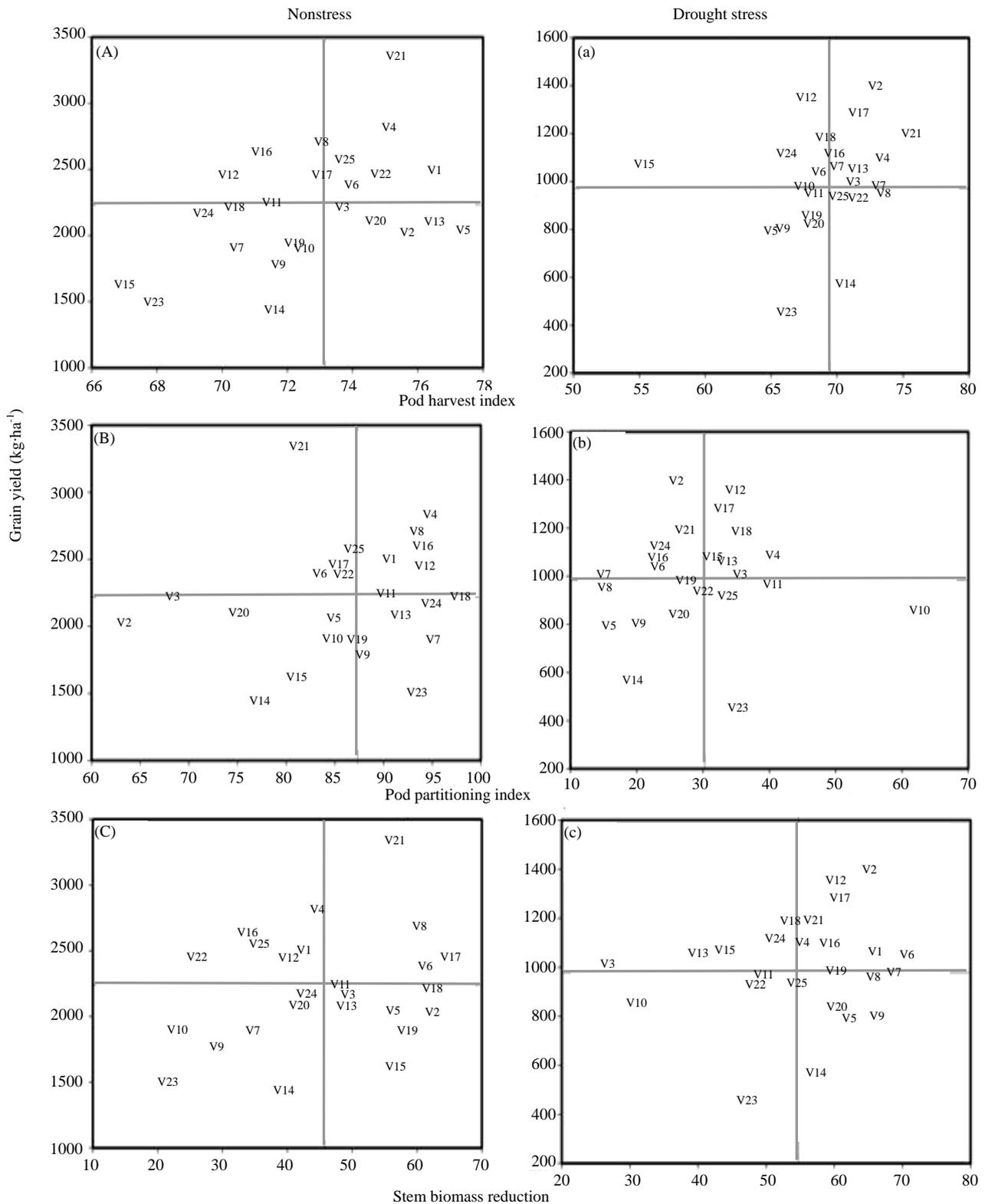For other traits, Red Wolayta, Omo-95 and Ibado were

Figure 2. Relationship between grain yield and photosynthate translocation and partitioning (PTP) traits: pod harvest index (A), (a), pod partitioning index (B), (b) and stem biomass reduction (C), (c) of the 25 common bean varieties evaluated in southern Ethiopia under drought stress and nonstress condition. Capitalized letters indicate nonstress conditions and non-capitalized letters indicate corresponding drought stress conditions. Pod partitioning index and stem biomass reduction were measured in Hawassa 2009 while pod harvest index was measured in all test environments (Hawassa 2008 and 2009 and in Amaro 2009).
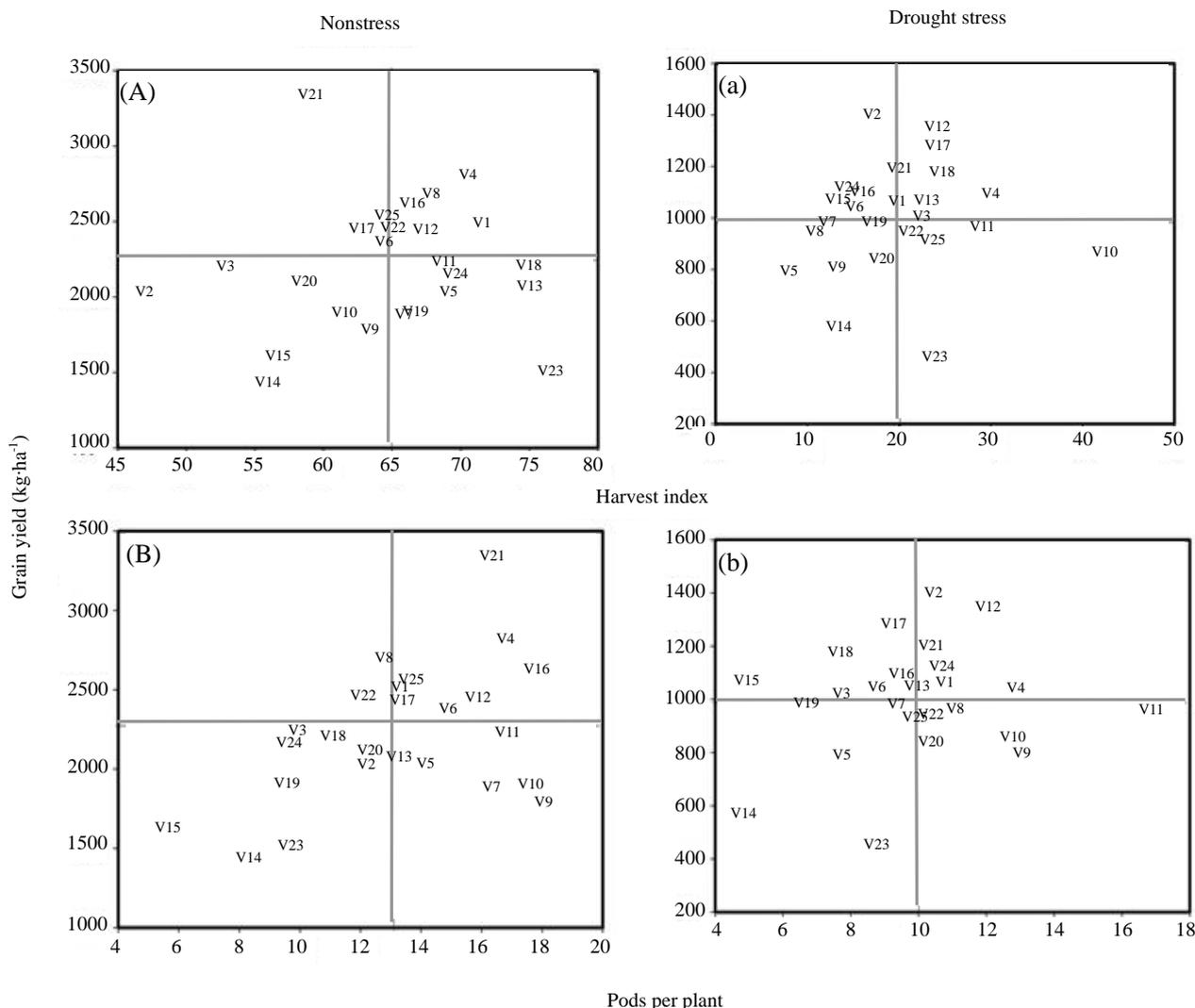
Figure 3. Relationship between grain yield with harvest index (A), (a) and pods per plant (B), (b) of 25 common bean varieties evaluated in southern Ethiopia under drought stress and nonstress conditions. Capitalized letters indicate nonstress conditions and non-capitalized letters indicate corresponding drought stress conditions, Harvest index was measured in Hawassa 2009 while pods per plant were measured in all test environments (Hawassa 2008 and 2009 and in Amaro 2009).

good in maintaining better grain yield with better pod partitioning index under both regimes whereas Argene showed outstanding performance for mobilization of photosynthates to pods under drought stress but poor ability to partition assimilated carbon onto the seeds in the development of higher yields.

Varieties like Omo-95, Dimitu and Hawassa Dume expressed better potential in mobilizing greater proportion of photosyntates from stem to pod and seed formation both under drought stress and nonstress condition as this was revealed by above average grain yield and stem biomass reduction values (**Figures 2(C), (c)**).

The relationship between grain yield and pods per plant showed that varieties Mex 142, Argene and Chore were outstanding in forming higher number of pods per

plant under both drought stress and nonstress but were not among the highest yielding varieties under both regimes (**Figures 3(B), (b)**).

3.4. Stability for Grain Yield and Other Traits

Table 5 presents mean grain yield over test environments and estimates of stability of the varieties for yield and other traits using cultivar superiority measure. Evaluating varieties based on mean grain yield and stability parameter identified Hawassa Dume as the best variety that combined high mean yield with best estimate for cultivar superiority measure. The drought adapted varieties Dimitu, Red Wolayta and Omo-95 from the Mesoamerican genepool and Ibado and AFR 702 from the Andean genepool were good in producing above-average

Table 5. Stability for grain yield, hundred seed weight, pod harvest index, pods per plant, seeds per plant, days to flowering and days to maturity of 25 common bean varieties evaluated under nonstress and drought stress environments in Hawassa and Amaro in southern Ethiopia over two years.

Varieties	Mean grain yield kg·ha^{-1}	Cultivar superiority measure (Pi)						
		Grain yield	HSW	PHI	PPP	SPP	DF	DM
Denkenesh	1745	373,549	44	5	11	1	13	11
Dimitu	1677	500,738	49	3	15	0	14	8
Melkadima	1620	651,707	3	5	20	1	1	2
Zebra	1930	217,144	25	4	7	1	5	9
Gofta	1430	781,755	20	10	11	1	2	5
Atndaba	1705	429,717	27	7	11	1	5	4
Awash Melka	1398	778,238	69	9	9	0	13	7
Naser	1789	322,901	48	5	11	0	3	8
Mex 142	1261	939,566	62	13	5	0	8	8
Argene	1351	848,860	75	8	5	0	8	9
Chore	1595	517,133	64	9	4	0	15	14
Red Wolayta	1912	285,915	48	11	7	0	11	9
Ayenew	1567	606,345	8	4	12	1	1	4
Cranskope	995	1,496,521	15	7	23	1	6	5
Red Kidney	1372	1,141,610	1	35	30	1	0	1
Awash-1	1889	230,671	64	9	7	0	4	8
Omo-95	1853	303,869	55	5	13	0	9	7
Ibado	1692	446,930	4	8	18	1	2	4
Goberasha	1444	766,991	12	7	21	1	2	6
Tabor	1474	682,599	49	6	13	0	13	10
Hawassa Dume	2217	75,337	34	2	11	0	4	7
SER-108	1642	533,097	31	4	12	1	2	3
Brown Speckled	926	1,775,030	24	14	18	1	4	2
AFR-702	1647	520,945	15	10	17	1	3	7
RAB-585	1693	367,199	40	5	13	0	2	4

Abbreviations for traits are the following: HSW = 100 seed weight (gm), PHI = Pod harvest index (%), PPP = Pods per plant, SPP = Seeds per pod, DF = Days to 50% flowering, DM = Days to 90% maturity.

grain yield but were not identified as stable by stability parameter values.

Andean varieties Red Kidney and Ibado, and Mesoamerican varieties Melkadima and Ayenew showed stability for expression of the trait 100 seed weight. Majority of the Mesoamerican varieties such as Dimitu, Zebra, Denkenesh, Nasir, Omo-95, Hawassa Dume, SER-108 and RAB-585 had best cultivar superiority estimates for pod harvest index indicating their stable performance across drought stress and nonstress environments in

translocating photosynthetically assimilated carbon from pod wall to the grain. None of the Andean varieties showed the same level stability for pod harvest index as the Mesoamerican varieties but Ibado, Goberasha and Cranskope had relatively lower cultivar superiority estimates for the trait. Varieties Argene, Mex 54 and Chore from Mesoamerican group showed stable performance for pods per plant whereas none from the Andean varieties. Majority of the Mesoamerican varieties such as Dimitu, Awasha Melka, Nasir, Mex142, Argene, Red Wo-

layta, Awash1, Omo-95, Tabor, Hawassa Dume and RAB-585 had best cultivar superiority estimates for expression the trait seeds per pod whereas none of the Andean varieties had best estimate for the trait. Mesoamerican varieties such as Melkadima, Gofta, Atendaba, Ayenew, SER-108 and RAB-585 and Andean varieties such as Red Kidney, Ibado and Brown Speckled recorded best estimates of cultivar superiority for both days to flowering and maturity.

The GGE biplot ranking of varieties based on both mean grain yield and stability performance also identified Hawassa Dume (V21) as superior (**Figure 4**) being located at the center of the concentric circles where an ideal cultivar should be. The terminal drought stress environment at Amaro in 2009 season (AMDS09) lacks correlation with the rest environments for varietal performance in grain yield. In this environment where the plants suffered a lot from terminal drought, Red Wolayta performed better. The Andean varieties Cranskope (V14) and Brown Speckled (V23) and Mesoamerican variety Mex 142 (V9) were inferior in both mean grain yield and stability performance being located at far end of the concentric circles for the ideal cultivar in the figure.

4. DISCUSSION

4.1. Choice of Test Environments in the Field Study
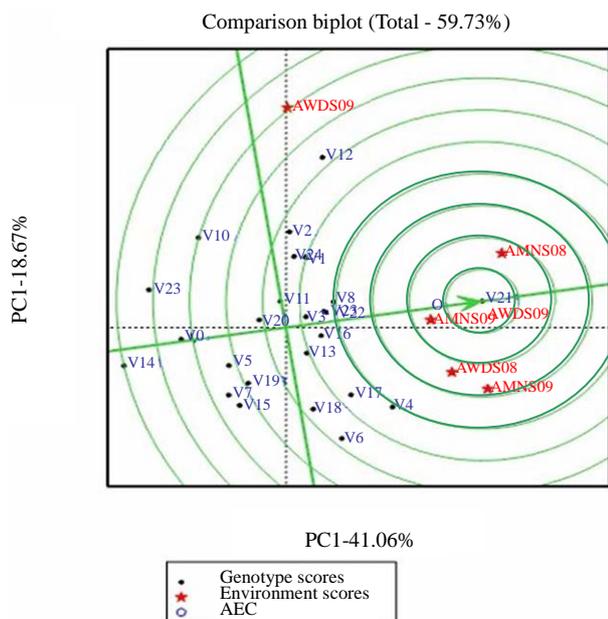
Assessing the level of drought tolerance of materials

Figure 4. GGE biplot ranking of varieties based on average grain yield and stability for grain yield across 6 environments under drought and nonstress conditions at the site in Hawassa over two years and Amaro in one year in southern Ethiopia during 2008 and 2009.

in a breeding program requires the comparison of performance in nonstress and stress environment experiments. This should be accomplished by a careful choice of test environments. This study assessed the level of drought tolerance in Ethiopian common bean varieties in field experiments using different sowing dates: early and late plantings to expose the crop to high and low seasonal rainfall during the growing season, respectively. The experiments were constructed to simulate some of the many possible forms of drought stress scenarios that may occur in common bean farming in Ethiopia, as farmers plant at different dates within the rainy season, themselves. In this study, the drought-stress effects were principally of two types: terminal drought-stress (occurring at the end of the plant's growth cycle) and intermittent (occurring on and off but especially around the vegetative to early reproductive period of plant development).

The induction of drought stress in some experimental sites is through control of irrigation rather than by changing the specific sowing date. However, this can only be done in the dry season and in experiment stations with controlled water supplies. Unfortunately, many of these experimental conditions are not available in developing countries and even where they are the dry season may present conditions that are extremely different than the ones faced by farmers in terms of pests, diseases and temperature or photoperiod regimes. Therefore, early sowing as a means of exposing the crops to high seasonal rainfall and late sowing for exposing the crops to low seasonal rainfall seems valid option for evaluating drought tolerance in many bean growing regions. In eastern Africa and especially in the Ethiopian growing season, water deficits can occurs any time in the crops growth cycle, however are more common as terminal drought towards the end of the season or intermittent drought half-way through the growing season. The advantage of planting at different sowing dates in the rainy season is that the researcher emulates the conditions faced by farmers in a rainfed agriculture.

In farmers' fields it is not uncommon to have a false start to the rainy season with a short rainy period followed by a longer dry spell that exposes the early sown crops to drought-stress at vegetative and flowering stages of the crop growth. We observed such a season in Hawassa 2008 and used this to switch experimental consideration of the stress and nonstressed treatments. In that case, the early-sown crop was exposed to intermittent drought stress while an extended rainfall period over the latter part of the season provided the late-sown crop with adequate moisture for better yield formation within the same cropping season.

However, with normal seasonal rainfall patterns as were observed in 2009, late-sown crops often experience terminal drought-stress. The data on drought intensity

index were severe for the drought-stress situations of Hawassa 2009 and Amaro 2009 cropping seasons. The drought conditions in those seasons as measured by drought severity indices were comparable with previous results reported for common beans grown under terminal drought in Ethiopia [4,20,21] and other drought studies reported in the tropics [30].

This indicated that designing experiments with different sowing dates can create a better opportunity for capturing consistent stress between experiments by exposing the crops to high and low seasonal rainfall during the growing season. An alternative is to use a rain-out shelter but this is very expensive for many experiment stations and limits the number of genotypes or plot sizes used in evaluation of the genotypes. Irrigation control is also not always reliable as a method of implementing drought-stress conditions especially when rains are intermittent as they are for most bean growing environments. The risk of overwatering the nonstress trial with irrigation plus rainfall is a real and present danger. Therefore, when managed drought stress either with a rain-out shelter covering the stress trial or with supplementary irrigation of nonstress trials is difficult to achieve, field testing with different sowing dates is a very valid technique. In such field testing, the number of sowing dates needs to be more than two to capture the possible drought patterns in the season. Reference [31] used five sowing dates to successfully explain phenological plasticity as mechanism of adaptation to rainfed environments in common bean grown in Colombia.

4.2. Prioritization of Drought Tolerance Measurements

Drought stress up-regulated or down-regulated trait expression in the varieties depending on which drought-tolerance measurement was considered (Table 2). Drought stress accelerated flowering and maturity of the varieties while causing reduced grain yield. The reduction in grain yield in drought-stress was higher or lower based mainly on photosynthate translocation and partitioning traits. Therefore, drought-stress decreased number of pods per plant, seeds per pod and seed weight (relatively unfilled seed) affecting yield more severely in some genotypes than in others. Similar results were reported by various authors [6-8,21,32,33].

The impact of drought stress on trait expression of the varieties varied. Some traits were more sensitive to drought stress than others. For instance, the effect of drought on photosynthate translocation and partitioning (PTP) traits was much more than that for yield component traits on the varieties studied (Table 2). This was attributed to differences between the varieties for adaptation to drought stress. In this study, the varieties that

showed better adaptation to drought stress used different mechanisms for displaying better yield potential. Drought tolerant varieties like Hawassa Dume maintained better photosynthate translocation and partitioning than the drought sensitive varieties like Brown Speckled or Red Wolayta under drought stress. Although Red Wolayta was not efficient in partitioning photosynthetically assimilated carbon from the pod walls to the seed; it was similar to Hawasa Dume in producing better grain yield by better stem biomass reduction, harvest index and pods per plant under stress (Figures 3 and 4).

In selection for increased drought tolerance, varietal difference may result from differences in many mechanism of adaptation like differences in growth, phenology, photosynthate acquisition, translocation and partitioning, and hydraulic characteristics of the root system [9,32, 34,35]. Tolerance is not a single trait but rather is the overall manifestation of the sum of the different mechanisms in the plant [3,10,18]. For example in some conditions earliness is a tolerance trait although in the sites and genotypes we evaluated early maturing varieties were not correlated with higher yields, but rather the opposite was true.

The multiple sub-trait nature of drought tolerance poses a challenge for plant breeders to pyramid the different mechanisms of drought tolerance. Furthermore, most of the individual drought-tolerance traits are also under complex polygenic control and to integrate these with grain yield and the other end-user preference characteristics like seed size and marketability is difficult. Our results, however, do indicate the relevance of continued high levels of photosynthate translocation and partitioning as an effective selection objective for improving drought adaptation in common bean. Reference [10] indicated common bean genotypes showing higher values of pod harvest index, pod partitioning index and a lower proportion of pod wall biomass were superior in their adaptation to drought stressed conditions. Better capacity to mobilize photoynthate to the developing grain improving yield potential under drought stress in common beans also reported by reference [36]. Stem reserve utilization for grain filling under drought stress is as an effective drought tolerance mechanism in crop plants [37]. Notably a breeding program has to prioritize and target those traits like overall yield which provide a genetic gain to farmers. In this regard, our result showing correlation of PTP and yield confirm that PTP can be a novel tolerance mechanism for targeting to improve drought adaptation breeding in common bean.

Increased or sustained harvestable yield is the main goal of common bean farming in Ethiopia and elsewhere. This goal is being challenged by drought stress linked with climate change. One of the strategies to minimize drought-induced yield reduction in common bean pro-

duction is through use of productive varieties adapted to drought stress conditions [32,34]. Many of the common bean varieties released/recommended for production by farmers in Ethiopia have been indirectly tested for adaptation to farmers prevailing conditions through conventional approaches and participatory breeding [4]. Selection for higher grain yield and yield stability across locations and over years has been the main criteria.

Quantifying the level of drought tolerance in available varieties in the field trials like the ones carried out here would help in designing a breeding strategy that incurporates traits related to drought tolerance in varieties that are attractive to common bean farmers to be grown by their diverse environments. In this study, the variety Red Wolayta representing the local farmer variety in the southern region of Ethiopia showed good adaptation to stress conditions. This is in contrast to reference [21] who reported Red Wolayta as susceptible variety to drought. This variety has been cultivated in marginal drought prone farming system probably for more than a century and could provide valuable alleles for adaptation to stressful environments in breeding programs. Moreover, variety like Hawassa Dume performed well under both drought stress and nonstress conditions and also showed better yield stability. Both varieties are indeterminate in their growth habit and apparently showed phenotypic plasticity through regrowth after drought shock. Longer growth and indeterminacy could be an important adaptation under drought stress.

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