Evaluation of common bean genotypes for drought tolerance

Tamires Ribeiro1*, Daiana Alves da Silva2, José Antônio de Fátima Esteves2, Cleber Vinicius Giaretta Azevedo3, João Guilherme Ribeiro Gonçalves2, Sérgio Augusto Morais Carbonell2, Alisson Fernando Chiorato2

1. Instituto Agronômico - Genética e Melhoramento Vegetal - Campinas (SP), Brazil.  
2. Instituto Agronômico - Centro de Grãos e Fibras - Campinas (SP), Brazil.  
3. Universidade Estadual Paulista Júlio de Mesquita Filho - Produção Vegetal - Melhoramento Genético Vegetal - Jaboticabal (SP), Brazil.

ABSTRACT: The aim of this study was to evaluate twelve genotypes of common bean for intermittent drought stress and for root growth angle. The water deficit experiments were conducted in 2015 and 2016 in a randomized block experimental design with split plots and three replications. Two treatments were applied: an irrigated treatment and a water deficit treatment, in which irrigation was suspended in pre-flowering and remained suspended up to the time at which the matrix potential of the soil was measured to be near –199 kPa. At the maximum point of water deficit, physiological and morphological traits were evaluated, and at physiological maturity, the yield compounds and grain yield. To evaluate root growth angle in 2016, a growth pouch system was used in a randomized block design, with five replications.

Water deficit reduced genotype performance for all the traits except leaf temperature and first pod height. In relation to grain yield, the genotypes SEA 5 and Carioca Precoce performed better under water restriction conditions in both evaluations. The genotype Gen TS 4-7 performed better in the 2015 evaluation, and Gen TS 3-1 and Gen TS 3-3 in 2016. SEA 5, Gen TS 3-1, and Carioca Precoce had the highest harvest indexes in 2015; and Gen TS 3-1, Gen TS 3-2, Gen TS 3-3, Gen P5-4-3-1, IAPAR 81, Carioca Precoce, and SEA 5 in 2016. SEA 5 and Carioca Precoce had the best root growth angle and were considered sources of tolerance to water deficit.

Key words: Phaseolus vulgaris, water deficit, grain yield, root growth angle.
INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) or dry edible bean, hereinafter bean, is one of the main agricultural crops in Brazil and in the world and plays an important role in the diet of African and Latin American populations as a source of plant protein, carbohydrates, dietary fiber, B complex vitamins, iron, calcium, and minerals (Beebe 2012).

The main producers of this legume, according to data from FAO (2014), are Myanmar (4,651,094 metric tons [t]), India (4,110,000 t), Brazil (3,294,586 t), the United States of America (1,311,340 t), Mexico (1,273,957 t), and the United Republic of Tanzania (1,114,500 t). However, production in these countries has tended to decline over the years due to increasingly significant climate changes and concerns over temperature and rainfall profiles that increase the occurrence and severity of drought events (Lobell et al. 2011). According to data from CONAB (2016), these events were also perceived in Brazil and led to a 21% decline in production in relation to the previous crop season.

To reduce the damage caused by water restriction and keep low production costs, plant breeding programs have concentrated on identifying and incorporating the drought tolerance trait in new bean genotypes, seeking to develop better adapted cultivars that produce even under unfavorable conditions.

In this regard, various studies have been undertaken to understand the mechanisms of drought tolerance. Root architecture can allow deeper and moister soil layers to be exploited to escape from water deficit, and thus it can be a promising trait for crop performance under stress conditions (Vadez 2014). Morphological traits, such as lower leaf area index, and physiological aspects, such as lower stomatal conductance, are also considered to be mechanisms of adaptation to water shortage, allowing the plant to reduce evapotranspiration area (Beebe et al. 2013; Rao 2014). Other important traits are biomass production, partitioning of dry matter to promote grain production, and harvest index (Rao et al. 2013). Plants have diverse mechanisms for response and adaptation to water stress; therefore, determination of their distinct morphological, physiological, and agronomic traits for drought tolerance is indispensable to ensure efficiency in the selection process (Beebe et al. 2013).

Under the hypothesis that bean genotypes have wide variability and respond differently to degrees of stress, the aim of this study was to evaluate the effect of water deficit applied to twelve bean genotypes with traits of commercial interest through evaluation of physiological, morphological, agronomic traits and root growth angle.

MATERIALS AND METHODS

Plant material

To carry out evaluations of drought tolerance (first-harvest, 2015 and 2016) and root growth angle (2016), the following genotypes were used: Gen TS 3-1, Gen TS 3-2, Gen TS 3-3, Gen TS 4-7, H96A31-P2-1-1-1-1, IAC Sintonia, Gen P5-4-3-1, Carioca Precoce, IAC Carioca Eté, and IAC Apuã (susceptible control), from the breeding program of the Instituto Agronômico (IAC); IAPAR 81, from the Instituto Agronômico do Paraná (IAPAR); and SEA 5 (tolerant control), from the Centro Internacional de Agricultura Tropical (CIAT).

Drought tolerance experiments

Two experiments were conducted of the first-harvest of 2015 and 2016 at the Experimental Center of the Santa Elisa Farm of the IAC in the municipality of Campinas, São Paulo, Brazil (22°54’ S, 47°03’ W, and altitude of 854 m). The experiments were conducted in the ground in a greenhouse through a randomized block design, with split plots and three replications. The plots consisted of the irrigated and water deficit treatments and the split plots consisted of the genotypes.

Before setting up the experiments, the chemical characteristics of the soil at the depth of 0 – 20 cm were determined according to Raij et al. (1997). Nitrogen fertilizer was applied at planting, consisting of 40 kg·ha⁻¹ N through urea and 40 kg·ha⁻¹ K₂O through KCl. Topdressing with urea was performed 25 days after sowing, applying 80 kg·ha⁻¹ N. Twenty four plants of each genotype were grown in 2.0 m rows, with a 0.50-m spacing between rows. Plots received two daily irrigations of three minutes, at 7:00 a.m. and 6:00 p.m., up to the R5 (pre-flowering) stage by an automated system with drip nozzles spaced at 0.15 m and flow rate of 0.90 L·h⁻¹. At this stage (R5), irrigation was interrupted in the plot under water deficit for 22 days in 2015 e 20 days in 2016, up to the time at which the matrix potential of the soil was measured to be near –199 kPa, indicating the absence of available water in the soil at a depth of 0.40 m.
During the experiments, the soil matric potential (Ψm) was monitored by moisture sensors, with readings taken by the Watermark meter.

At the time of maximum water deficit, the following evaluations were performed: stomatal conductance (Porometer Type AP4 – Delta T Devices), leaf temperature (Telatemp model AG-42D, Telatemp, Fullerton, CA), relative chlorophyll index (SPAD-502 Plus – Konica Minolta), leaf area (area meter - Model LI-3100C - LI-COR), total shoot dry matter and leaf dry matter. After that, irrigation was continued in the plot under water deficit, and at physiological maturity of the plants, the following evaluations were made: plant height, first pod height, 100 seed weight and grain yield. Harvest index (HI = seed biomass dry weight at harvest/total shoot biomass dry weight at mid-podfilling × 100) and the water stress intensity index (WSI = [1 – (Stress/No stress)] 100) were calculated as described by Beebe et al. (2013). The data obtained were evaluated by the R statistical program through individual analysis of variance. Mean values were compared by the Scott-Knott test at p > 0.05 probability.

Root angle experiment

The experiment was conducted in 2016 at the Experimental Center of the Santa Elisa Farm of the IAC in the municipality of Campinas, São Paulo, Brazil. A randomized block experimental design was used, with five replications, according to the methodology of Vieira et al. (2008). The seeds of the bean genotypes were pre-germinated and the seedlings were placed in a growth pouch system. This system consisted of a 28 × 38 cm sheet of Germitest paper with neutral pH, which was folded in the middle and inserted in a polyethylene bag (growth pouch system). In the upper part of the polyethylene bag, a V cut was made to accommodate the seedling. The growth pouches were supported crosswise by plastic channels in the upper part of rectangular glass vessels. The open part of the polyethylene was turned to the inside of the vessel, allowing the Germitest paper to remain in direct contact with the nutrient solution and allowing it to touch the seedling roots through capillarity.

The nutrient solution used was developed in the common bean plant breeding program of the IAC, described by Silva et al. (2014), without any kind of abiotic stress. The nutrient solution was prepared at half strength (50%) since the complete solution is used for developed plants and this study was carried out with common bean seedlings. The pH was maintained between 6 and 7 and electrical conductivity at 620.56 uS·cm⁻¹. The vessels were lined with aluminum foil so as to maintain the roots in darkness and placed in a climate-controlled chamber (temperature of 26 °C during the day and 20 °C at night; 12 hour photoperiod) for seven days. Seven days after transplanting, the angles (°) in relation to vertical of the intact roots in the growth pouches were determined using a protractor, considering the relation between the basal roots and the main growth axis. The data obtained were evaluated by the R statistical program through analysis of variance, and comparison of mean values by the Scott-Knott test at p > 0.05 probability.

RESULTS AND DISCUSSION

In the 2015 evaluation, with a water stress intensity index of 71%, performance of the genotypes declined for all the traits evaluated, except for leaf temperature (LT) and first pod height (FPH). Analysis of variance showed a significant difference for water treatment for all the traits and, in regard to genotypes, for leaf area (LA), leaf dry matter (LDM), total shoot dry matter (TDM), plant height (PH), first pod height (FPH), 100 seed weight (100SW), and grain yield (GY), indicating genetic variability among the genotypes (Tables 1 and 2). The mean square of the water treatment × genotype interaction exhibited a significant difference for GY, showing different performance of the genotypes from the imposition of water deficit (Tables 1 and 2).

In the 2016 evaluation, the water stress intensity index was 68%, leading to lower performance of genotypes for all the evaluated traits, except LT and FPH. Analysis of variance showed a significant difference for water treatment for all the traits and between genotypes for relative chlorophyll index (RCI), LA, LDM, TDM, PH, FPH, 100SW, and GY (Tables 1 and 2). The mean square of the water treatment × genotype interaction exhibited significance for 100SW and GY, showing different performance of the genotypes from the imposition of water deficit (Tables 1 and 2).

The coefficients of variation (CV%) of both experiments were considered to be of low to medium magnitude, showing the reliability of the results obtained (Tables 1 and 2).

Water restriction led to a significant reduction of 46% in the RCI of the genotypes evaluated in 2015, lowering the content of leaf pigments in the plants subjected to this restriction. The joint test presented an overall mean of 33.68 un.
SPAD (Table 3), with no significant difference being detected between the genotypes. In the 2016 evaluation the RCI overall mean observed in the joint test was 27.78 un. SPAD (Table 4) and there was a significant reduction of 18% in RCI. The genotypes Gen P5-4-3-1 (22.64 un. SPAD), Gen TS 3-1 (23.00 un. SPAD), IAC Sintonia (24.80 un. SPAD) and SEA 5 (25.97 un. SPAD) differed from the others with the lowest RCI (Table 4). The results obtained in this study are in agreement with those presented by Darkwa et al. (2016), who observed lower RCI values and reported that this is a characteristic manifested in plants grown under water deficit; loss of chlorophyll is common, which is normally followed by progressive decline in the photosynthetic ability of the plants. Nevertheless, the genotypes evaluated in this study showed similar behavior in relation to RCI in the two evaluations, except for Gen P5-4-3-1, Gen TS 3-1, IAC Sintonia, and SEA 5 in 2016, making it difficult to select superior genotypes through this characteristic.

For stomatal conductance ($g_s$), there was a significant reduction of 82% in 2015 and 53% in 2016. The joint test presented an overall mean of 167.30 mmol·m$^{-2}$·s$^{-1}$ in 2015 and 96.04 mmol·m$^{-2}$·s$^{-1}$ in 2016 (Tables 3 and 4), nevertheless, significant differences between the genotypes were not detected. Although reduction in stomatal conductance protects plants from desiccation, it negatively affects photosynthesis, reducing the CO$_2$ availability for the photosynthetic process and, consequently, biomass accumulation is inhibited (Ribeiro et al. 2013; Sales et al. 2015). In this respect, regulation of

### Table 1. Mean squares of analysis of variance for chlorophyll index (RCI), stomatal conductance ($g_s$), relative leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), and total shoot dry matter (TSDM) of 12 bean genotypes (G) that underwent two water treatments (WT), irrigated and water deficit. Harvest 2015 and 2016, Campinas, São Paulo, Brazil.

| Source of variation | DF | Mean squares |
|---------------------|----|--------------|
|                     |    | RCI (un. SPAD) | $g_s$ (mmol·m$^{-2}$·s$^{-1}$) | LT (°C) | LA (dcm$^2$) | LDM (g) | TSDM (g) |
|                     |    | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| Block               | 2  | 36.139 | 127.5376 | 0.2044 | 15.1552 | 1.9755 | 0.4405 | 0.1115 | 0.6977 | 0.1354 | 0.4792 | 0.0146 | 0.0515 |
| WT                  | 1  | 7244.869** | 562.242* | 55.761** | 253.923* | 105.851** | 19.812** | 12.550** | 37.955** | 17.180** | 2.812** | 2.933** |
| Residue a           | 2  | 36.2194 | 13.8143 | 0.3952 | 15.4593 | 15.0555 | 1.0516 | 0.0812 | 0.0015 | 0.1172 | 0.0738 | 0.0098 | 0.0087 |
| Genotype            | 11 | 45.8966 | 55.534** | 0.0829 | 1.4852 | 1.0958 | 0.6943 | 0.3872* | 0.627** | 0.4398* | 0.083** | 0.042* |
| WT x G              | 11 | 40.9646 | 41.0925 | 0.1605 | 2.8502 | 0.9097 | 0.2406 | 0.1095 | 0.1203 | 0.1262 | 0.2035 | 0.0173 | 0.0144 |
| Residue b           | 44 | 30.9183 | 20.6599 | 0.2012 | 3.7352 | 1.3060 | 0.4733 | 0.1604 | 0.1047 | 0.1983 | 0.1378 | 0.0218 | 0.0235 |
| Total               | 71 | 17.85 | 13.38 | 13.34 | 41.74 | 1774 | 3.91 | 4.20 | 0.54 | 13.47 | 13.44 | 6.14 | 6.56 |
| CVa (%)             |    | 17.85 | 13.38 | 13.34 | 41.74 | 1774 | 3.91 | 4.20 | 0.54 | 13.47 | 13.44 | 6.14 | 6.56 |
| Cvb (%)             |    | 16.49 | 16.36 | 9.51 | 20.51 | 5.22 | 2.62 | 5.90 | 4.58 | 1795 | 18.35 | 9.11 | 10.74 |

** and * significant at 1% and at 5% probability by the F test, respectively.

### Table 2. Mean squares of analysis of variance for plant height (PH), first pod height (FPH), number of pods per plant (NPP), number of seeds per pod (NSPod), number of seeds per plant (NSP), 100 seed weight (100SW), and grain yield (GY), of 12 bean genotypes (G) that underwent two water treatments (WT), irrigated and water deficit. Harvest 2015 and 2016, Campinas, São Paulo, Brazil.

| Source of variation | DF | Mean squares |
|---------------------|----|--------------|
|                     |    | PH (cm) | FPH (cm) | NPP (un.) | NSPod (un.) | NSP (un.) | 100SW (g) | GY (Kg·ha$^{-1}$) |
|                     |    | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| Block               | 11 | 118.190 | 0.0793 | 0.0059 | 11.9062 | 0.1478 | 0.0432 | 0.1069 | 1.8256 | 0.0619 | 0.5691 | 2.9159 | 3935.12 | 0.1368 | 0.2802 |
| WT                  | 2  | 700.93** | 7.6866** | 73.750* | 101.53* | 172.55* | 2.4047* | 19.71** | 6.924* | 6.862* | 92.93** | 629.59** | 9918** | 51.663** | 34.303** |
| Residue a           | 1  | 6.865 | 0.0019 | 1.137 | 5.6562 | 0.0012 | 0.0032 | 0.1500 | 0.0267 | 0.0049 | 0.1363 | 1.6890 | 274.881 | 0.1177 | 0.0222 |
| Genotype            | 2  | 1581.92** | 0.480** | 8.588** | 40.59** | 0.1191 | 0.0272 | 0.3421 | 0.1098** | 0.0266 | 1.976** | 52.98** | 7159.23** | 0.261** | 0.726** |
| WT x G              | 11 | 179.656 | 0.1176 | 3.1094 | 11.3797 | 0.1258 | 0.0408 | 0.2612 | 0.0733 | 0.0319 | 1.1206* | 4.2211 | 4959.14** | 0.261** | 0.352** |
| Residue b           | 11 | 43.100 | 0.0417 | 1.9150 | 7.6903 | 0.0690 | 0.0454 | 0.2603 | 0.0372 | 0.0196 | 0.4240 | 1.5653 | 1787.15 | 0.0710 | 0.0710 |
| Total               | 44 | 71    | 5.04 | 12.98 | 18.56 | 1.56 | 3.99 | 9.02 | 10.00 | 3.28 | 9.88 | 5.36 | 11.13 | 6.56 | 3.25 |

** and * significant at 1% and at 5% probability by the F test, respectively.
stomatal opening by genotypes tolerant to water deficit allows reduction in transpiration and the operability of the photosynthetic apparatus, making crop production possible under unfavorable conditions.

For leaf temperature (LT), there was a significant increase of 5.29 °C in the leaves of plants grown under water deficit in 2015 and 2.43 °C in 2016. The joint test presented an overall mean of 21.87 °C in 2015 and 26.17 °C in 2016 (Tables 3 and 4). Leaf temperature is directly related to gs, which declines under water restriction conditions, decreasing leaf transpiration and dissipation of latent heat, hindering cooling of plants (Kumar and Portis Jr. 2009). Fernandes et al.

| Genotype    | RCI (un. SPAD) | gs (mmol m⁻² s⁻¹) | LT (°C) | LA (dm²) | LDM (g) | TDM (g) | PH (cm) | FPH (cm) | 100SW (g) | GY (kg ha⁻¹) |
|-------------|----------------|---------------------|---------|----------|---------|---------|--------|---------|-----------|--------------|
| Gen TS 3-1  | 35.70a         | 137.83a             | 21.80a  | 8.52b    | 1.85b   | 8.04a   | 33.94c | 11.39b  | 25.89b    | 13370.44a    | 340.74Bb     |
| Gen TS 4-7  | 32.22a         | 187.60a             | 21.79a  | 9.29b    | 1.92b   | 8.74a   | 59.64b | 13.03a  | 30.43a    | 1533.33a     | 559.28Ba     |
| IAC H96A31P2-1-1-1 | 34.29a          | 188.44a             | 21.20a  | 12.48b   | 2.22b   | 5.89b   | 33.89c | 11.17b  | 19.24d    | 1342.81Ac    | 184.67Bb     |
| IAC Sintonia| 31.12a         | 176.42a             | 22.34a  | 8.97b    | 1.89b   | 7.60a   | 59.95b | 12.67a  | 25.07b    | 1374.07Aa    | 366.67Bb     |
| Gen P5-4-3-1| 35.43a         | 138.74a             | 21.52a  | 11.20b   | 21.08b  | 6.85a   | 60.50b | 12.92a  | 23.21c    | 1425.39a     | 281.48Bb     |
| Carioca Precoce | 32.59a         | 138.35a             | 21.64a  | 15.31a   | 2.89a   | 8.75a   | 64.46b | 13.25a  | 23.99b    | 1907.41Aa    | 400.00Bb     |
| IAC -Apuã   | 36.62a         | 182.43a             | 21.57a  | 19.17a   | 4.26a   | 11.14a  | 65.00b | 12.28b  | 25.77b    | 1170.37Ac    | 299.56Bb     |
| SEA 5       | 32.39a         | 208.45a             | 22.52a  | 8.67b    | 2.06b   | 7.87a   | 34.95c | 10.59b  | 27.22b    | 1166.67Aa    | 585.19Ba     |
| Mean value  | 33.71          | 167.30              | 21.87   | 10.94    | 2.26    | 7.81    | 51.92  | 12.46   | 24.21     | 1376.23      | 387.27       |

Different lowercase letters in the columns indicate statistical differences (p < 0.05) by the Scott-Knott test between the genotypes under the same water condition, and different uppercase letter represent statistical differences between the irrigation treatments.

| Genotype    | RCI (un. SPAD) | gs (mmol m⁻² s⁻¹) | LT (°C) | LA (dm²) | LDM (g) | TDM (g) | PH (cm) | FPH (cm) | 100SW (g) | GY (kg ha⁻¹) |
|-------------|----------------|---------------------|---------|----------|---------|---------|--------|---------|-----------|--------------|
| Gen TS 3-1  | 23.00 b        | 78.70 a             | 26.62 a | 9.23 b   | 0.98 b  | 5.74 a  | 34.67 b| 11.34 b | 18.22 Ab   | 1746.4a      | 735.04 Ab    |
| Gen TS 3-2  | 28.25 a        | 102.93a             | 25.65 a | 11.25 b  | 1.25 b  | 3.88 a  | 34.83 b| 12.50 b | 16.95 Ab   | 1740.4a      | 259.81 Bb    |
| Gen TS 3-3  | 29.67 a        | 96.67 a             | 26.00 a | 8.38 b   | 1.00 b  | 4.92 a  | 34.50 b| 15.50 a | 20.31 Aa   | 1659.4a      | 335.15 Bb    |
| Gen TS 4-7  | 31.50 a        | 93.83 a             | 26.26 a | 10.13 b  | 1.00 b  | 4.17 a  | 36.00 a| 12.00 b | 24.75 Aa   | 1451.4a      | 229.63 Bb    |
| IAC H96A31P2-1-1-1 | 29.39 a         | 107.08a             | 26.08 a | 29.36 a  | 1.67 a  | 5.27 a  | 34.67 b| 11.17 b | 14.96 Ab   | 5114 Ba      | 342.81 Ac    | 102.26 Bc    |
| IAC Sintonia| 24.80 b        | 98.58 a             | 26.63 a | 12.98 b  | 1.75 a  | 5.99 a  | 59.34 a| 14.00 b | 21.32 Aa   | 184.11 Aa    | 709.85 Ab    | 272.96 Ba    |
| Gen P5-4-3-1| 22.64 b        | 161.67a             | 26.75 a | 12.36 b  | 0.84 b  | 3.83 a  | 4700 b | 8.83 b  | 16.50 Ab   | 1312 Aa      | 643.00 Ab    | 165.52 Bb    |
| IAPAR 81    | 30.70 a        | 100.20 a            | 26.25 a | 11.03 b  | 0.85 b  | 3.77 a  | 53.50 a| 11.83 b | 20.29 Aa   | 1429 Ba      | 746.93 Ab    | 259.26 Ba    |
| Carioca Precoce | 32.73 a         | 102.86 a            | 25.86 a | 17.80 a  | 1.42 a  | 7.84 a  | 70.67 a| 12.34 b | 20.88 Aa   | 963.5 b      | 1101.15 Aa   | 302.74 Ba    |
| Carioca Eté | 30.85 a        | 77.33a              | 26.03 a | 20.56 a  | 1.84 a  | 5.14 a  | 61.8 a | 15.34 a | 19.13 Aa   | 1654.4a      | 1056.48 Aa   | 183.78 Bb    |
| IAC -Apuã   | 29.18 a        | 103.33 a            | 25.88 a | 21.60 a  | 1.42 b  | 4.10 a  | 60.83 a| 18.42 a | 21.61 Aa   | 713 Bb       | 980.63 Aa    | 93.89 Bc     |
| SEA 5       | 25.97 b        | 85.66 a             | 26.08 a | 14.43 b  | 1.22 b  | 5.55 a  | 34.67 b| 10.50 b | 20.83 Aa   | 1736 Aa      | 1082.11 Aa   | 360.41 Ba    |
| Mean value  | 27.78          | 96.04               | 26.17   | 13.98    | 1.27    | 4.98    | 46.88 | 12.82   | 17.58      | 140.00       | 803.41       | 250.83       |

Different lowercase letters in the columns indicate statistical differences (p < 0.05) by the Scott-Knott test between the genotypes under the same water condition, and different uppercase letter represent statistical differences between the irrigation treatments.
(2015) reported a 2 °C increase in leaf temperature of cowpea subjected to a 10-day period of water deficit. The authors did not find a significant difference between genotypes, just as the result of the present study, which made selection of tolerant genotypes by means of this characteristic unfeasible.

For leaf area (LA) there was significant decrease of 65% in the plants grown in the treatment under water deficit in 2015 and of 56% in 2016. This can be explained by the decrease in plant moisture content, which causes reduction in cell turgor pressure. Ghanbari et al. (2013) evaluated eight common bean genotypes and found a 27% reduction in LA in plants grown under water deficit conditions. In the present study, the genotypes that showed the biggest reductions in LA in the 2015 evaluation were IAC Apuã (75%), Carioca Precoce (73%), Gen TS 3-1 (71%), H96A31P2-1-1-1-1 (70%), SEA 5 (69%), Gen TS 4-7 (69%), and Carioca Eté (69%). The joint test presented an overall mean of 10.94 dm² and the genotypes that showed the largest LA were IAC Apuã (19.17 dm²) and Carioca Eté (15.31 dm²) (Table 3). In the 2016 evaluation, that showed the largest LA were IAC Apuã (19.17 dm²) and Gen P5-4-3-1 (18.83 dm²) and the genotypes presented an overall mean of 13.98 dm² and genotypes that had LA greater than the reduction reported by Moraes et al. (2010), who found a 5% reduction in PH in plants grown for a period of 15 days under water deficit. For FPH in the two evaluations, the genotypes under water deficit exhibited first pod height greater than the genotypes of the irrigated treatment, except for the genotype SEA-5 (10.59 cm) in 2015 and genotypes H96A31-P2-1-1-1-1 (11.17 cm) and IAPAR 81 (11.83 cm) in 2016, suggesting that this variable can be considered as indicating the occurrence of pods abortion of the plant's lower part. The joint test presented an overall mean of 12.46 cm in 2015 and 12.82 cm in 2016 for FPH (Tables 3 and 4). In 2015, the genotype Carioca Precoce exhibited the highest FPH (14.78 cm) and the genotype SEA-5, the lowest (10.59 cm) (Table 3). In 2016, the genotype IAC Apuã (18.42 cm) exhibited the highest FPH and Gen P5-4-3-1 (8.83 cm), the lowest (Table 4). FPH is an important trait when considering mechanical harvest because lower pod height and high lodging rates make harvest with self-propelled machines unfeasible. The ideal plant for mechanical harvest has a height of more than 50 cm, resistance to lodging, and pods concentrated in the upper 2/3 of the plant. This is a characteristic that should be considered in release of a new common bean cultivar to ensure acceptance by producers. In the present study, the genotypes that had PH greater than 50 cm in 2015 were Carioca Precoce (79.28 cm), IAC Apuã (65.00 cm), Carioca Eté (64.45 cm), Gen P5-4-3-1 (60.94 cm), IAPAR 81 (60.50 cm), IAC Sintonia (59.95 cm) and Gen TS 4-7 (59.84 cm) (Table 3); and in 2016 were Carioca Precoce (70.67 cm), Carioca Eté (61.84 cm), IAC Apuã (60.83 cm), Carioca Precoce (59.34 cm) and IAPAR 81 (53.50 cm) (Table 4); however these genotypes had pods concentrated below the upper 2/3 of the plant in the two evaluations (2015 and 2016) (Tables 3 and 4).

For total shoot dry matter (TDM), there was a significant reduction of 62% in the treatment under water deficit in 2015 and 43% in 2016. This reduction is directly related to limitation of cell expansion, giving rise to plants of reduced growth and lower yield. The reductions in PH indicated in this study were greater than the reduction reported by Moraes et al. (2010), who found a 5% reduction in PH in plants grown for a period of 15 days under water deficit. For FPH in the two evaluations, the genotypes under water deficit exhibited first pod height greater than the genotypes of the irrigated treatment, except for the genotype SEA-5 (10.59 cm) in 2015 and genotypes H96A31-P2-1-1-1-1 (11.17 cm) and IAPAR 81 (11.83 cm) in 2016, suggesting that this variable can be considered as indicating the occurrence of pods abortion of the plant's lower part. The joint test presented an overall mean of 12.46 cm in 2015 and 12.82 cm in 2016 for FPH (Tables 3 and 4). In 2015, the genotype Carioca Precoce exhibited the highest FPH (14.78 cm) and the genotype SEA-5, the lowest (10.59 cm) (Table 3). In 2016, the genotype IAC Apuã (18.42 cm) exhibited the highest FPH and Gen P5-4-3-1 (8.83 cm), the lowest (Table 4). FPH is an important trait when considering mechanical harvest because lower pod height and high lodging rates make harvest with self-propelled machines unfeasible. The ideal plant for mechanical harvest has a height of more than 50 cm, resistance to lodging, and pods concentrated in the upper 2/3 of the plant. This is a characteristic that should be considered in release of a new common bean cultivar to ensure acceptance by producers. In the present study, the genotypes that had PH greater than 50 cm in 2015 were Carioca Precoce (79.28 cm), IAC Apuã (65.00 cm), Carioca Eté (64.45 cm), Gen P5-4-3-1 (60.94 cm), IAPAR 81 (60.50 cm), IAC Sintonia (59.95 cm) and Gen TS 4-7 (59.84 cm) (Table 3); and in 2016 were Carioca Precoce (70.67 cm), Carioca Eté (61.84 cm), IAC Apuã (60.83 cm), Carioca Precoce (59.34 cm) and IAPAR 81 (53.50 cm) (Table 4); however these genotypes had pods concentrated below the upper 2/3 of the plant in the two evaluations (2015 and 2016) (Tables 3 and 4).

For 100 seed weight (100SW), the genotypes under water restriction exhibited a significant reduction of 22% in 2015...
and 20% in 2016. Reductions in 100SW found in this study were greater than those reported by Assefa et al. (2015), who indicated reduction of 9%; however, these authors reported sporadic rains during the field experiment, which may have favored the crop. Beebe et al. (2008) emphasized that tolerant genotypes exhibited better grain filling and grain quality, ensuring crop yield under unfavorable conditions. In the present study, the joint test presented an overall mean of 24.21 g in 2015 and the genotypes that stood out in 100SW were Gen TS 4-7 (30.43 g), SEA 5 (27.22 g), Gen TS 3-3 (25.89 g), IAC-Apuã (25.77 g), IAC Sintonia (25.07 g), Gen TS 3-1 (24.33 g), and IAC Carioca Eté (23.99 g) (Table 3). The genotypes that stood out in 100SW in 2016 in the treatment under water deficit were: IAC Sintonia (18.41 g), Gen TS 3-1 (17.46 g), Gen TS 3-2 (17.40 g), SEA 5 (17.36 g), Gen TS 3-3 (16.59 g), Carioca Eté (16.54 g), Gen TS 4-7 (14.51 g), IAPAR 81 (14.29 g) and Gen P5-4-3-1 (13.12 g) (Table 4).

The imposition of water deficit led to a significant reduction of 72% in GY in 2015 and a 69% reduction in 2016. Padilla-Chacón et al. (2017) reported similar results, indicating reduction from 41% to 76% in yield of common bean genotypes grown under water deficit conditions. Asfaw and Blair (2014) also presented similar results using three environments in their evaluation, reporting mean reduction of 55% in common bean yield under water deficit. This emphasizes the relationship between climate conditions and crop yield, which, according to Gris et al. (2015), is the characteristic most affected under these conditions. In 2015, the highest yielding genotypes in the treatment under water deficit were: SEA 5 (585.19 kg·ha⁻¹), Gen TS 4-7 (559.26 kg·ha⁻¹), and Carioca Precoco (540.74 kg·ha⁻¹) (Table 3). Under water deficit conditions, these higher yielding genotypes exhibited the greatest reduction in LA; and genotypes SEA 5 and Carioca Precoco, the greatest reduction in TDM. In 2016, the genotypes with high reduction in TDM also had GY above the overall mean for the treatment under water deficit (Gen TS 3-3 (444.52 kg·ha⁻¹), SEA 5 (444.52 kg·ha⁻¹), Gen TS 3-3 (335.15 kg·ha⁻¹), and Carioca Precoco (302.74 kg·ha⁻¹)) (Table 4). The genotypes Carioca Precoco and SEA 5 exhibited similar values of TDM in the treatment under water deficit in the two evaluations (Carioca Precoco: 4.69 g in 2015 and 4.67 g in 2016; and SEA 5: 3.55 g in 2015 and 3.27 g in 2016) and had GY above the overall mean for the treatment under water deficit (Table 3 and 4). In 2015, the genotype TS 3-1 had the lowest value for TDM (1.39 g) in the treatment under water deficit and, consequently, a GY (366.67 kg·ha⁻¹) below the overall mean (Table 3). However, the same genotype in 2016 had twice the amount of TDM (2.97 g), and GY (444.52 kg·ha⁻¹) above the overall mean for the treatment under water deficit (Table 4), indicating the importance of the evaluation of these characteristics in selection of genotypes tolerant to water deficit. In contrast, some genotypes exhibited high values of TDM, and GY below the overall mean for the treatment under water deficit. According to Cortés et al. (2013), these results can be explained by variation in the dynamic of remobilization of biomass for pod and grain production; this is an important parameter that was recently integrated in selection of common bean genotypes tolerant to water deficit. Determination of remobilization of biomass for grain production is an important factor for selection of common bean genotypes tolerant to water deficit, and can be achieved by the harvest index (HI) (Beebe et al. 2013).

In regard to the Harvest Index (HI) in 2015 for the treatment under water deficit, the following genotypes stood out: SEA 5 (93%), Gen TS 3-1 (86%), Carioca Precoco (65%), IAC Carioca Eté (58%), Gen TS 4-7 (54%) and Gen TS 3-2 (50%). Lower HI for water deficit was shown by the genotypes: IAC Sintonia (45%), IAC Imperador (40%), Gen TS 3-3 (37%), IAPAR 81 (33%), IAC Apuã (32%) and IAC H96A31- P2-1-1-1-1 (29%). The genotypes SEA 5, Carioca Precoco, IAC Carioca Eté, and Gen TS 4-7 exhibited GY above the overall mean under water deficit conditions; and the genotypes Carioca Precoco and Gen TS 4-7 exhibited TDM above the overall mean for water deficit (Table 3). The genotype Gen TS 3-1 showed high HI, however, it had GY below the overall mean (Table 3). This result can be explained by genotype Gen TS 3-1 having had the lowest value of TDM, which hurt its GY under water deficit conditions.

In 2016, the genotypes with the highest HI for the treatment under water deficit were IAPAR 81 (86%), Gen TS 3-1 (84%), Gen TS 3-3 (81%), Gen TS 3-2 (80%), Carioca Precoco (64%), Gen P5-4-3-1 (62%), SEA 5 (62%) and IAC Sintonia (58%). Lower HI for water deficit was shown by the genotypes: Gen TS 4-7 (43%), IAC H96A31- P2-1-1-1-1 (42%), Carioca Eté (40%) and IAC Apuã (30%). The genotypes Gen TS 3-1, Gen TS 3-3, Gen TS 3-2, SEA 5, and Carioca Precoco had GY above the overall mean, and the genotype Carioca Precoco had the highest TDM in the treatment under water deficit (Table 4). The genotype Gen TS 3-1 once more exhibited higher HI and, in this evaluation, exhibited TDM and GY above the overall mean for the treatment under water deficit (Table 4).
In the results obtained, we can highlight the importance of evaluation of TDM, HI, and GY in selection of genotypes tolerant to water deficit since genotypes with lower mean values of TDM may exhibit lower GY, even with high HI, just as genotypes with higher mean values of TDM may exhibit lower HI and lower GY, which are highly affected by water deficit. In the two evaluations, the genotypes SEA 5, Gen TS 3-1, and Carioca Precoce had higher HI. Sea 5 and Carioca Precoce had higher HI, TDM and GY under conditions of water deficit for the two evaluations. The SEA 5 genotype was also highlighted in the study of Polania et al. (2016), with combined significantly higher canopy biomass and with higher values of grain yield under drought conditions. The authors emphasized that the genotypes resistant to drought are associated with higher canopy biomass a more efficient photosynthe remobilization to pod formation and grain production, as observed in the present study. Similar results were observed by Gonçalves et al. (2015), who recommended the genotype SEA 5 for breeding programs aimed at drought tolerance, due to its general combining ability, considering grain yield. Lower HI for water deficit was shown by the genotype IAC Apuã in 2015 and 2016, with GY below the overall mean for the two evaluations (Table 3 and 4).

In relation to evaluation of root growth angle (RGA), there was significant difference among genotypes, indicating genetic variability and allowing selection using this trait (Table 5).

When we consider drought tolerance, roots play an important role, providing for better use and uptake of the resources available in the soil. According to Hossain et al. (2015), drought tolerant genotypes have a greater root angle and greater growth and branching, reaching deeper soil layers, whereas genotypes susceptible to water deficit have more superficial roots. In this respect, evaluation of root growth angle can assist and ease selection of tolerant genotypes since larger angles indicate deeper roots, allowing better absorption of water from the soil (Uga et al. 2015).

For RGA, the overall mean was 51°, and the following genotypes stood out: SEA 5 (74°), Carioca Precoce (61°), Gen TS 4-7 (59°), Gen P5-4-3-1 (56°), Gen TS 3-3 (54°), Gen TS 3-1 (54°), and IAC Sintonia (50°) (Fig. 1). The SEA 5 genotype (tolerant to water deficit) had the highest RGA, as well as GY and HI above the mean for the treatment under water deficit in the two evaluations (2015 and 2016).

Table 5. Mean squares of analysis of variance of 12 bean genotypes evaluated in regard to root growth angle.

| Analysis variances | DF | Mean squares |
|--------------------|----|--------------|
| Block              | 4  | 19.1         |
| Genotype           | 11 | 701.4**      |
| Residue            | 44 | 34.9         |
| Total              | 59 | 11.68        |

**significant at 1% probability by the F test, respectively.

Figure 1. Performance of 12 bean genotypes with regard to root growth angle. Genotypes: 1 = Gen TS 3-1; 2 = Gen TS 3-2; 3 = Gen TS 3-3; 4 = Gen TS 4-7; 5 = H96A31-P2-1-1-1-1; 6 = IAC Sintonia; 7 = Gen P5-4-3-1; 8 = IAPAR 81; 9 = Carioca Precoce; 10 = IAC Carioca Eté; 11 = IAC Apuã (susceptible control); and 12 = SEA 5 (tolerant control).
Similar results were observed by Polania et al. (2016), who showed that the genotype SEA 5 had higher performance under drought stress and was associated with better canopy biomass that could be related to deeper root system, favoring the grain yield. The authors also emphasized that the genotype SEA 5 have mechanisms that can maintain a competitive level of water balance, allowing more effective use of water and the grain formation and filling during stress. The genotypes IAC Apuã (susceptible to water deficit) and H96A31-P2-1-1-1-1 had lower RGA, GY and HI below the overall mean in the two evaluations (Fig. 1). The Carioca Precoce genotype had RGA above the overall mean (Fig. 1) and stood out for TDM, HI, and GY in the two evaluations (Tables 3 and 4), emphasizing the importance of evaluation of these characteristics for selection of genotypes tolerant to water deficit. A similar result was presented by Polania et al. (2017), who identified the genotypes SEA 15, NCB 280, SCR 16, SMC 141, BFS 29, BFS 67, and SER 119 as possible parent lines for improvement of the drought tolerance trait for common bean, as they had a deeper root system, greater biomass, and ability to remobilize photoassimilates to grain production. The authors emphasized that common bean yield under water deficit conditions is directly related to root length and vigor, allowing access to water from deeper soil layers. In the present study, in the 2015 evaluation the genotype Gen TS 4-7 stood out in regard to TDM, HI, GY, and RGA; in 2016, the genotypes Gen TS 3-1 and Gen TS 3-3 stood out. In the 2015 and 2016 evaluation the genotypes SEA 5 and Carioca Precoce stood out.

Induction of water deficit was effective in discriminating genotypes in the two crop years, resulting in significant differences in development of plants in regard to water treatments for all the traits evaluated and between the genotypes for leaf area, leaf dry matter, total shoot dry matter, plant height, first pod height, 100 seed weight, and grain yield.

Evaluation of root growth angle indicated genetic variability, making genotype discrimination possible.

The traits of shoot dry matter, harvest index, grain yield, and root growth angle were effective for selection of genotypes tolerant to water deficit.

The cultivars Carioca Precoce and Sea 5 exhibited better performance than the other genotypes under water deficit conditions. The superior performance of these genotypes under drought stress could be associated with better canopy biomass accumulation and a vigorous root system providing better utilization of deeper soil, associated with effective remobilization of photosynthates from vegetative structures for pod production and grains.

ACKNOWLEDGMENTS

The authors thank the Fundação Amparo à de Pesquisa do Estado de São Paulo (FAPESP) for financial support.

ORCID IDs

T. Ribeiro
https://orcid.org/0000-0001-5630-9128

D. A. Silva
https://orcid.org/0000-0002-4211-3308

J. A. F. Esteves
https://orcid.org/0000-0001-7690-8937

Cl. V. G. Azevedo
https://orcid.org/0000-0001-5486-4953

J. G. R. Gonçalves
https://orcid.org/0000-0003-1568-572X

S. A. M. Carbonell
https://orcid.org/0000-0003-2964-972X

A. F. Chiorato
https://orcid.org/0000-0002-7004-4717
REFERENCES

Asfaw, A. and Blair, M. W. (2014). Quantification of drought tolerance in Ethiopian common bean varieties. Agricultural Sciences, 5, 124-139. https://doi.org/10.4236/as.2014.52016

Assefa, T., Wu, J., Beebe, S., Rao, I. M., Marcomin, D. and Claude, R. J. (2015). Improving adaptation to drought stress in small red common bean: phenotypic differences and predicted genotypic effects on grain yield, yield components and harvest index. Euphytica, 3, 477-489. https://doi.org/10.1007/s10681-014-1242-x

Beebe, S. (2012). Common bean breeding in the tropics. In J. Janick (Ed.), Plant Breeding Review. Hoboken: John Wiley. https://doi.org/10.1002/9781118358566.ch5

Beebe, S. E., Rao, I. M., Blair, M. W. and Acosta-Gallegos, J. A. (2013). Phenotyping common beans for adaptation to drought. Frontiers in Physiology/Plant Physiology, 4, 35. https://doi.org/10.3389/fphys.2013.00035

Beebe, S. E., Rao, I. M., Cajiao, I. and Grajales, M. (2008). Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. Crop Science, 48, 582-592. https://doi.org/10.2135/cropsci2007.04.0404

[CONAB] Companhia Nacional de Abastecimento (2016). Boletim de monitoramento verão Set 2016; [accessed 2017 September 12]. https://www.conab.gov.br/info-agro/safras/graos/monitoramento-agricola/item/6140-boletim-de-monitoramento-verao-set-2016

Cortés, A. J., Monserrate, F. A., Ramírez-Villegas, J., Madriñán, S. and Blair, M. W. (2013). Drought Tolerance in Wild Plant Populations: The Case of Common Beans (Phaseolus vulgaris L.). PloS ONE, 8, e62898. https://doi.org/10.1371/journal.pone.0062898

Darkwa, K., Ambachew, D., Mohammed, H., Asfaw, A. and Blair, M. W. (2016). Evaluation of common bean (Phaseolus vulgaris L.) genotypes for drought stress adaptation in Ethiopia. The Crop Jornal, 4, 367-376. https://doi.org/10.1016/j.cj.2016.06.007

[FAO] Food and Agriculture Organization of the United Nations (2014). FAOSTAT; [accessed 2017 January 10]. http://www.fao.org/faostat/en/#data/QC/visualize

Fernandes, F. B. P., Lacerda, C. F., Andrade, E. M., Neves, A. L. R. and Sousa, C. H. C. (2015). Efeito de manejo de solo no déficit hídrico, trocas gasosas e rendimento do feijão-de-corda no semiárido. Revista Ciência Agronômica, 46, 506-515. https://doi.org/10.5935/1806-6690.20150032

Ghanbari, A. A., Shakiba, M. R., Toorchi, M. and Choukan, R. (2013). Morpho-physiological responses of common bean leaf to water deficit stress. European Journal of Experimental Biology, 3, 487-492.

Gonçalves, J. G. R., Chiorato, A. F., Silva, D. A., Esteves, J. A. F., Bosetti, F. and Carbonell, S. A. M. (2015). Combining ability in common bean cultivars under drought stress. Bragantia, 74, 149-155. https://doi.org/10.1590/1678-4499.0345

Hossain, M. M., Lam, H-M. and Zhang, J. (2015). Responses in gas exchange and water status between drought-tolerant and -susceptible soybean genotypes with ABA application. The Crop Journal, 3, 500-506. https://doi.org/10.1016/j.cj.2015.09.001

Kumar, A., Li C. and Portis Jr., A. R. (2009). Arabidopsis thaliana expressing a thermostable chimeric Rubisco activase exhibits enhanced growth and higher rates of photosynthesis at moderately high temperatures. Photosynthesis Research, 3, 143-53. https://doi.org/10.1007/s10110-009-9438-y

Lobell, D. B., Bänziger, M., Mogorokosho, C. and Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change, 1, 42-45. https://doi.org/10.1038/nclimate1043

Moraes, W. B., Martins Filho, S., Garcia, G. O., Caetano, S. P. and Moraes, W. B. (2010). Seleção de genótipos de feijoeiro à seca. Idesia, 28, 53-59. https://doi.org/10.4067/S0718-34292010000200006

Müller, B. S. F., Sakamoto, T., Silveira, R. D. D., Zambussi-Carvalho, P. F., Pereira, M., Pappas Jr., G. J., Costa, M. M. C., Guimarães, C. M., Pereira, W. J., Brondani, C. and Vianello-Brondani, R. P. (2014). Differentially expressed genes during flowering and grain filling in common bean (Phaseolus vulgaris) grown under drought stress conditions. Plant Molecular Biology Reporter, 32, 438-451. https://doi.org/10.1007/s11105-013-0651-7

Padilla-Chacón, D., Martínez-Barajas, E., García-Esteva, A., Leal-Delgado, R., Kohashi-Shibata, J. and Peña-Valdivia, C. B. (2017). Biomass remobilization in two common bean (Phaseolus vulgaris L.) cultivars under water restriction. South African Journal of Botany, 112, 79-88. https://doi.org/10.1016/j.sajb.2017.05.015
Polania, J., Poschenrieder, C., Rao, I. and Beebe, B. (2017). Root traits and their potential links to plant ideotypes to improve drought resistance in common bean. Theoretical and Experimental Plant Physiology, 29, 143-154. https://doi.org/10.1007/s40626-017-0090-1

Polania, J., Rao, I. M., Cajiao, C., Rivera, M., Raatz, B. and Beebe, S. (2016). Physiological traits associated with drought resistance in Andean and Mesoamerican genotypes of common bean (Phaseolus vulgaris L.). Euphytica, 210, 17-29. https://doi.org/10.1007/s10681-016-1691-5

Raij, B., Cantarella, H., Quaggio, J. Á. and Furlani, A. M. C. (1997). Recomendações de adubação e de calagem para o Estado de São Paulo. Campinas: Instituto Agronômico/Fundação IAC.

Rao, I. M., Beebe, S., Polania, J., Ricaurte, J., Cajiao, C., Garcia, R. and Rivera, M. (2013). Tepary bean as a model for improvement of drought resistance in common bean? African Crop Science Society, 21, 265-281.

Rao, I. M. (2014). Advances in improving adaptation of common bean and Brachiaria forage grasses to abiotic stress in the tropics. In Pessarakli M (Ed.), Handbook of plant and crop physiology. (p. 847-889). Boca Raton: CRC Press.

Ribeiro, R. V., Machado, R. S., Machado, E. C., Machado, D. F. S. P., Magalhães Filho, J. R. and Landell, M. G. A. (2013). Revealing drought resistance and productive patterns in sugarcane genotypes by evaluating both physiological responses and stalk yield. Experimental Agriculture, 49, 212-224. https://doi.org/10.1017/S0014479712001263

Sales, C. R. G., Marchiori, P. E. R., Machado, R. S., Fontenele, A. V., Machado, E. C., Silveira, J. A. G. and Ribeiro, R. V. (2015). Photosynthetic and antioxidant responses to drought during the sugarcane ripening. Photosynthetica, 53, 547-554. https://doi.org/10.1007/s11099-015-0146-x

Silva, D. A., Esteves, J. A. F., Messias, U., Teixeira, A., Gonçalves, J. G. R., Chiorato, A. F. and Carbonell, S. A. M. (2014). Advances in improving adaptation of common bean and Brachiaria forage grasses to abiotic stress in the tropics. In Pessarakli M (Ed.), Handbook of plant and crop physiology. (p. 847-889). Boca Raton: CRC Press.

Sales, C. R. G., Marchiori, P. E. R., Machado, R. S., Fontenele, A. V., Machado, E. C., Silveira, J. A. G. and Ribeiro, R. V. (2015). Photosynthetic and antioxidant responses to drought during the sugarcane ripening. Photosynthetica, 53, 547-554. https://doi.org/10.1007/s11099-015-0146-x

Silva, D. A., Esteves, J. A. F., Messias, U., Teixeira, A., Gonçalves, J. G. R., Chiorato, A. F. and Carbonell, S. A. M. (2014). Efficiency in the use of phosphorus by common bean genotypes. Scientia Agricicola, 71, 232-239. https://doi.org/10.1590/S0103-90162014000300008

Uga, Y., Kitomi, Y., Ishikawa, S. and Yano, M. (2015). Genetic improvement for root growth angle to enhance crop production. Breeding Science, 65, 111-119. https://doi.org/10.1270/jsbbs.65.111

Vadez, V. (2014). Root hydraulics: the forgotten side of roots in drought adaptation. Field Crops Research, 165, 15-24. https://doi.org/10.1016/j.fcr.2014.03.017

Vieira, R. F., Carneiro, J. E. S. and Lynch, J. P. (2008). Root traits of common bean genotypes used in breeding programs for disease resistance. Pesquisa Agropecuária Brasileira, 43, 707-712. https://doi.org/10.1590/S0100-204X2008000600006