Screening Andean Diversity Panel Dry Bean Lines for Resistance to Bacterial Brown Spot Disease Under Field Conditions in South Africa

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Abstract

Bacterial brown spot (BBS) disease caused by *Pseudomonas syringae* pv. *syringae* is an important disease of dry bean (*Phaseolus vulgaris* L.), with grain yield losses of 55% reported in South Africa. This study aimed to identify BBS disease-resistant genotypes from 415 Andean Diversity Panel (ADP) dry bean lines and 5 check cultivars under field conditions across three sites in South Africa: Warden and Middelburg under natural infestation and Potchefstroom under artificial inoculation. Plants at Potchefstroom were inoculated with *P. syringae* pv. *syringae* using three isolates at 21, 28, and 36 days after planting, and disease scoring was done at 7, 14, and 21 days after inoculation following a modified 1 to 9 International Centre for Tropical Agriculture (CIAT) scale. The BBS severity percentage and the area under the disease progress curve (AUDPC) were applied to quantify the reaction of bean genotypes to BBS disease. The study identified 17.2% of evaluated germplasm as resistant and 45.3% as moderately resistant. Genotypes ADP-0592, ADP-0790, ADP-0120, and ADP-0008 were selected for both resistance and high seed yield across the three environments. Genotypes ADP-0546, ADP-

0630, ADP-0120, and ADP-0279 were selected for both high yield and resistance at Warden, whereas ADP-0038, ADP-0721, and ADP-0790 were selected for both traits at Middelburg, and lastly, ADP-0120 and ADP-0079 were selected for both traits at Potchefstroom. The best genotypes selected for both high yield and BBS resistance had grain yield >1.45 t ha⁻¹ across sites and >1.85 t ha⁻¹ at individual sites, and they out yielded the best-performing check cultivar (1.13 t ha⁻¹) and the grand mean yield (0.87 t ha⁻¹) across sites. The AUDPC had a strong negative correlation ($r = -0.55$, $P < 0.001$) with grain yield at Potchefstroom. Medium-seeded genotypes showed a lower AUDPC than the large-seeded genotypes, and indeterminate genotypes showed a lower AUDPC than determinate genotypes. The genotypes selected for resistance and yield can be utilized in future dry bean improvement efforts for the South African bean market.

Keywords: Andean Diversity Panel (ADP) dry bean lines, correlation among related traits, reaction to BBS disease, screening

Sub-Saharan Africa is a nutritionally unstable region with reported malnutrition-related challenges (Dlamini et al. 2017), where millions of people depend on cereal-based foods that are deficient in proteins, vitamins, and several other micronutrients. Most people in the region face occasional household food shortages leading to hunger and starvation (Singh and Miklas 2015). The adoption of legumes with increased levels of proteins can boost nutritional security in the region (Singh and Miklas 2015). Dry bean (*Phaseolus vulgaris* L.) provides between 10 and 25% of protein and 71% of starch (Broughton et al. 2003) to the daily diet in the region (Broughton et al. 2003). The average yield in South Africa is approximately 1.40 t ha⁻¹ (Dlamini et al. 2017), which is low compared with that of North America (approximately 3.00 t ha⁻¹) (Food and Agriculture Organization of the United Nations 2014; Kimani et al. 2005).

Dry bean cultivation is affected by several biotic constraints, including bacterial brown spot (BBS), a bacterial disease that occurs worldwide, and it is particularly serious in South Africa, being present in all of the dry bean-growing regions (Muedi et al. 2015b). BBS disease has been extensively described in the United States, Brazil, and Canada (Harveson and Schwartz 2007; Singh and Schwartz 2010). The disease, caused by *Pseudomonas syringae* pv. *syringae*, is seedborne and largely affects the foliage and to a

smaller extent, the pods (Navarro et al. 2007). Also, it is especially severe when beans are grown in a monocropping system (Muedi et al. 2015b). It has been reported that BBS disease can cause up to 55% of yield losses where conditions are conducive to the disease (Muedi et al. 2015b; Serfontein 1994). Symptoms may initially appear as small water-saturated wounds on leaves and pods and subsequently, develop into elliptical, necrotic brown wounds encircled by a thin yellow-green border part (Kimani et al. 2005; Muedi et al. 2015b). Sources of infection include infected seed, heavy wind, contaminated farm implements, and soil (Harveson et al. 2015). Infected seed is an important way of dissemination of *P. syringae* pv. *syringae* (Kimani et al. 2005). Heavy wind can promote infection by helping to create wounds on plants or disperse bacteria, but wind does not provide a bacterial source to cause infection. However, rain and overhead irrigation have similarly been recognized as effective dispersion methods of *P. syringae* pv. *syringae* (Navarro et al. 2007). Humidity >95% and temperatures between 28 and 32°C are favorable conditions for BBS disease, and these conditions are common in the central and eastern regions of South Africa, where dry beans are widely grown on a commercial scale (Muedi et al. 2015b).

BBS disease control includes planting of certified disease-free seed, crop rotation, resistant cultivars, and control on host plants (Navarro et al. 2007). Resistant cultivars have been recognized as the best way to control the disease in a sustainable way (Harveson et al. 2015). An important study of the inheritance of BBS resistance was undertaken by Navarro et al. (2007). This research used the *P. syringae* pv. *syringae* seedling stem inoculation in a dry bean-segregating recombinant inbred lines (RIL) population of the cross Belneb RR-1 × A55 and found a number of genomic regions situated on several linkage groups that were related to BBS resistance (Navarro et al. 2007). The large-seeded dry and green bean cultivars originating from the Andean gene pool are highly susceptible to BBS disease, whereas the small- and medium-seeded cultivars of Mesoamerican gene pool origin are more tolerant to bacterial disease (Singh and Schwartz 2010). The identification of genetic resources resistant

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to BSS disease will assist in the development of cultivars with improved resistance to BBS to the benefit of South African farmers. This study aimed to screen 415 Andean Diversity Panel (ADP) dry bean lines and 5 checks cultivars for resistance to BBS disease under field conditions in South Africa.

Materials and Methods

Genetic materials and experimental sites. In total, 415 ADP dry bean lines and 5 check cultivars maintained by the Agricultural Research Council–Grain Crops Institute Program were included in the study. The ADP consisted of genotypes from the Andean gene pool, local commercial cultivars, breeding lines, and landraces from Africa and the Americas (Cichy et al. 2015). These materials were screened for resistance to BBS disease under artificial inoculation at Potchefstroom and under natural inoculation at Warden and Middelburg during the 2017/2018 growing season. The trials were planted on 18, 19, and 20 December 2017 at Middelburg, Warden, and Potchefstroom, respectively. Potchefstroom is located in North West province of South Africa at an altitude of 1,349 m, latitude 26.74° S, and longitude 27.08° E. Warden is located in Free State province, and it is at an altitude of 1,720 m, latitude 28.31° S, and longitude 29.12° E. Middelburg is located in Mpumalanga province at an altitude of 1,277 m, latitude 31.47° S, and longitude 25.03° E (Muedi et al. 2015b).

Weather data. The weather data across three experimental sites are indicated in Table 1. The mean temperatures ranged from 25.0°C (Warden) to 28.2°C (Middelburg), whereas Middelburg had the lowest rainfall (346.34 mm), and Warden had the highest rainfall (687.7 mm).

Experimental design. The experimental layout was an α -lattice design with three replicates, with 10 incomplete blocks in each replicate at all of the three locations. The replications were separated by a 5-m-wide block planted with the susceptible cultivar Teebus RR-1 as the spreader and source of inoculum. Each incomplete block had 42 plots with ADP lines, and the blocks were separated by a 2-m pathway. Each plot had one row of 5 m in length. Each row had 75 plants, with in-row distance of 7.5 cm and interrow distance of 76 cm. Two border rows (Teebus RR-1) were planted around the four sides of the experiment, and the trial was weeded mechanically. Irrigation was applied at Potchefstroom when required, whereas Middelburg and Warden were dry land. The nitrogen, phosphorus, and potassium fertilizers were applied to the fields at rates of 42.3, 22.3, and 18.4 kg ha⁻¹, respectively.

BBS disease inoculation. Middelburg and Warden have a history of BBS disease, and the experiments relied on natural inoculation, whereas at Potchefstroom, artificial inoculum of *P. syringae* pv. *syringae* was applied. The inoculum was made from 48- to 72-h-old cultures grown on King's B medium (Johnsen and Nielsen 1999). Three isolates (BV 6.3, BV 3.3.2, and BV 27.1) with the highest level of aggression based on bean pod assays were mixed and suspended in water for inoculation. The suspension was adjusted to 1 × 10⁸ CFU/ml, and it was used immediately for the field inoculation (Muedi et al. 2015a). To increase the development of BBS, the experiment was irrigated before the inoculum application on the leaves, and plants were spray inoculated at 21, 28, and 36 days after planting

through a mechanical inoculum sprayer (Stihl Mist Blower SR 430) during the morning hours.

Data collection. The BBS severity was evaluated 7 days after the initial inoculation or initial appearance of disease symptoms, and the rating was done weekly for 3 consecutive weeks (Muedi et al. 2015b). The BBS severity was evaluated based on the percentage of diseased leaf area for the total plot using a modified International Centre for Tropical Agriculture (CIAT) scale from 1 (resistant or immune) to 9 (very susceptible or diseased) (van Schoonhoven and Pastor-Corrales 1987). The BBS severity scores were converted to percentages using log transformation as follows: 1 = 5%, 2 = 15%, 3 = 25%, 4 = 35%, 5 = 45%, 6 = 55%, 7 = 65%, 8 = 75%, and 9 = 85%. The BBS severity percentages were used to calculate the area under disease progress curve (AUDPC) (Muedi et al. 2015b). Several other traits were measured, namely days to flowering (DF), days to maturity (DM), and grain yield. The growth habit and seed size were the secondary data. The DF, DM, and grain yield data were collected from the experiments across three evaluated sites, whereas the seed size and the growth habit data were obtained through the secondary data.

Data analysis. The data were analyzed using unbalanced analysis of variance in Genstat 18th edition (Gilmour et al. 2015). Means were separated by the least significant difference (LSD) at $P = 0.05$. The model for the combined analysis of variance of multi-environment trials (equation 1) was

$$Y_{ijkl} = \mu + G_i + E_j + R_{k(j)} + B_{l(jk)} + GE_{ij} + \varepsilon_{ijkl} \quad (1)$$

where Y_{ijkl} is the response of the i th genotype in the j th environment, the k th replication within the environment, and the l th incomplete block within the replication; μ is the grand mean; G_i is the effect of the i th genotype, $i = 1, 2, \dots, 420$; E_j is the effect of the j th environment, $j = 1, 2, 3$; $R_{k(j)}$ is the replication effect $k = 1, 2, 3$; $B_{l(jk)}$ is the block effect $l = 1, 2, \dots, 10$; GE_{ij} is the genotype × environment interaction effect; and ε_{ijkl} is the random error. The relationship between BBS reaction, growth habit, and seed size was performed using the secondary data and the primary data of the AUDPC.

Disease reaction and AUDPC. The AUDPC for each genotype was calculated using the percentage severity scores as a dependent variable (Campbell and Madden 1990), and it was calculated as follows:

$$\text{AUDPC} = \sum_{i=1}^n [(X_{i+1} + X_i)/2] \times [t_{i+1} - t_i] \quad (2)$$

where X_i is the disease severity rating (percentage) at date i ; X_{i+1} is the disease severity rating (percentage) at date $i + 1$; $t_{i+1} - t_i$ is the number of days between the i th and the $(i + 1)$ th date; and n is the total number of observations.

The AUDPC data were subjected to analysis of variance, and means were separated using Fischer's LSD ($P \leq 0.05$). Furthermore, the correlation analysis between reaction to BBS, DF, DM, AUDPC, and grain yield was performed for the Potchefstroom evaluation trial.

Table 1. The weather data of three experimental sites^a

Month	Potchefstroom		Warden		Middelburg	
	Temperature (°C)	Rainfall (mm)	Temperature (°C)	Rainfall (mm)	Temperature (°C)	Rainfall (mm)
October 2017	26.39	56.13	24.89	49.53	24.90	28.45
November 2017	29.12	69.34	27.05	82.04	29.30	19.56
December 2017	29.29	62.48	26.06	208.79	32.01	10.03
January 2018	31.04	47.24	28.39	110.49	32.74	111.51
February 2018	27.68	68.33	26.75	66.80	30.68	77.47
March 2018	27.54	58.93	23.63	131.52	29.21	22.10
April 2018	25.33	35.56	22.90	12.95	24.75	62.74
May 2018	22.78	11.28	20.32	25.65	21.61	14.48
Average	27.40	—	25.00	—	28.15	—
Total	—	409.29	—	687.77	—	346.34

^a The source of the data is the Agricultural Research Council (2018).

Results

Combined analysis of variance across three sites. The combined analysis of variance for BBS severity and grain yield (tons hectare⁻¹) is presented in Table 2. The mean squares for genotype, environment, genotype and environment interaction (GEI) were significant ($P < 0.001$) for both BBS severity and grain yield (tons hectare⁻¹). The variation for BBS severity was partitioned for environment, genotype, and GEI as 4.32, 28.08, and 49.29% of the total sum of squares, respectively, whereas for grain yield (tons hectare⁻¹), the variation for BBS severity was partitioned for environment, genotype, and GEI as 20.92, 24.93, and 44.95%, respectively. The mean BBS severity and yield were 38.85% and 0.87 t ha⁻¹, respectively. Significant GEI effects for BBS disease ($P < 0.001$) and grain yield ($P < 0.001$) indicated different rankings in each environment, and thus, further analysis was done to establish which genotypes performed better or worse in particular environments.

Analysis of variance for individual sites. The analysis of variance for BBS severity and grain yield (tons hectare⁻¹) for the individual sites is presented in Table 3. There were significant differences ($P < 0.05$) among genotypes for BBS severity, AUDPC, and grain yield (tons hectare⁻¹) at three sites (Table 3). Genotype variations for BBS severity were 73.23, 69.86, and 72.80% of the total sum of squares in Warden, Middelburg, and Potchefstroom, respectively. However, genotype variations for grain yield were 86.68, 84.66, and 84.47% of the total sum of squares in Warden, Middelburg, and Potchefstroom, respectively. The genotype variation for AUDPC was 72.80% of the total sum of squares at Potchefstroom (Table 3). The variations for the blocks were 4.39, 20.61, and 10.54% for BBS severity and 1.94,

10.71, and 7.12% for grain yield of total sum square in Warden, Middelburg, and Potchefstroom, respectively. The variations for the replication were 0.63, 0.06, and 0.18% for BBS severity and 0.09, 0.02, and 0.04% for grain yield in Warden, Middelburg, and Potchefstroom, respectively. The AUDPC variation were 10.54 for block and 0.18 for replication of total sum square.

Mean of BBS severity and grain yield across three sites. The mean BBS severity and grain yield of the 10 best-performing genotypes and the 5 worst-performing genotypes across three environments are presented in Table 4. The mean BBS severity ranged from 15 (ADP-0592) to 63.15% (ADP-0310), whereas the grain yield of genotypes ranged from 0.32 t ha⁻¹ (ADP-0577) to 1.66 t ha⁻¹ (ADP-0097). Four genotypes of the 10 best-performing genotypes, namely ADP-0592, ADP-0790, ADP-0120, and ADP-0008, had both low BBS severity and high grain yield across the three environments (Table 4). Genotypes selected across three sites had a mean grain yield above the grand mean (0.87 t ha⁻¹) and the best-performing local check cultivar Kamiesberg (1.13 t ha⁻¹) and a mean BBS severity below the grand mean (39.85%) and the best-performing local check cultivar (31.67%) (Table 4).

Mean of BBS disease severity and grain yield for each site. The 10 best-performing genotypes for mean BBS severity, AUDPC, and grain yield and the 10 worst-performing genotypes at the three sites are presented in Table 5. Genotypes with BBS severity <25.0% in three sites were regarded as resistant to BBS disease, genotypes with BBS severity between 25.0 and 55.0% were regarded as moderate, and genotypes with BBS severity >55.0% were regarded as susceptible to the BBS disease. As a result, 8.4, 45.3, and 46.3% of genotypes were selected as resistant, moderate, and susceptible reaction to BBS disease, respectively, in Warden. In Middelburg, 35.7% of genotypes showed a resistant reaction, whereas 35.7 and 28.7% showed moderate and susceptible reaction to BBS disease, respectively. At Potchefstroom, 7.5% were resistant to BBS disease, and 54.9 and 37.6% were moderate and susceptible, respectively. The AUDPC ranged from 1,948.30 for ADP-0733 to 105.00 for ADP-0798. The mean BBS severity rates were 44.1, 36.7, and 38.68%, whereas the mean grain yields were 0.8, 0.64, and 1.16 t ha⁻¹ for Warden, Middelburg, and Potchefstroom, respectively.

Relation between BBS disease reaction and grain yield. The grain yield ranged from 2.47 t ha⁻¹ (ADP-0546) to 0.18 t ha⁻¹ (ADP-0746) in Warden, from 2.13 t ha⁻¹ (ADP-0239) to 0.17 t ha⁻¹ (ADP-0644) in Middelburg, and from 2.31 t ha⁻¹ (ADP-0517) to 0.16 t ha⁻¹ (ADP-0242) in Potchefstroom (Table 5). The genotypes ADP-0546, ADP-0630, ADP-0120, and ADP-0279 had both low mean BBS severity and the highest grain yield of the 10 best-performing genotypes in Warden. The genotypes ADP-0038, ADP-0721, and ADP-0790 had both low mean BBS severity and the highest grain yield of the 10 best-performing genotypes in Middelburg. Genotypes ADP-0120 and ADP-0079 had low mean BBS severity, low AUDPC, and the highest grain of the 10 best-performing

Table 2. Combined analysis of variance showing mean squares for bacterial brown spot (BBS) severity and grain yield across three experimental sites^a

Source	DF	BBS severity		Yield (t ha ⁻¹)	
		SS	MS	SS	MS
Environment	2	37,248.18	18,624.09 ^b	179.05	89.52 ^b
Env.Rep	6	1,945.12	324.19 ^b	0.33	0.06 ^c
Env.Rep.Block	81	119,435.95	1,327.07 ^b	47.13	0.52 ^b
Genotypes	419	241,983.45	587.34 ^b	213.42	0.52 ^b
Genotype × environment	838	347,444.15	421.66 ^b	358.07	0.44 ^b
Residual	2,433	113,829.28	46.05	57.96	0.02
Total	3,779	861,886.28	226.45	855.96	0.23
LSD			10.86		0.25
CV			17.03		17.63
Mean			39.85		0.87

^a Yield indicates the grain yield (tons hectare⁻¹). CV, percentage coefficient of variation; DF, days to flowering; LSD, least significant difference; MS, mean of square; SS, sum square; Env.Rep, replications within environments; Env.Rep.Block, incomplete blocks within replications and environments.

^b $P < 0.001$.

^c $P < 0.01$.

Table 3. Analysis of variance showing mean for bacterial brown spot (BBS) disease severity, relative area under disease progress curve (AUDPC), and grain yield for individual sites^a

Source	DF	Warden				Middelburg				Potchefstroom					
		BBS severity		Grain yield		BBS severity		Grain yield		BBS severity		AUDPC		Grain yield	
		SS	MS	SS	MS	SS	MS	SS	MS	SS	MS	SS	MS	SS	MS
Rep	2	1,301.18	650.59 ^b	0.17	0.09 ^c	246.02	123.01	0.04	0.02	397.92	198.96 ^d	175,481.00	87,741.00 ^d	0.12	0.06
Rep.block	27	10,165.99	338.87	4.09	0.14 ^b	85,335.19	2,844.51 ^b	23.50	0.78 ^b	23,934.77	797.83 ^b	10,555,233.00	351,841.00 ^b	19.54	0.65 ^b
Gen	419	151,379.37	367.43 ^b	174.4	0.42 ^b	279,982.54	679.57 ^b	183.2	0.45 ^b	158,065.70	383.65 ^b	69,706,972.00	169,192.00 ^b	213.90	0.52 ^b
Residual	811	43,882.54	53.26	15.80	0.02	35,222.22	42.75	9.90	0.01	34,724.51	42.14	15,313,511.00	18,584.00	32.27	0.04
Total	1,259	206,729.08	163.04	194.4	0.15	400,785.97	316.08	216.7	0.17	217,122.90	171.23	95,751,197.00	75,514.00	265.8	0.21
LSD			11.70		0.22		10.48		0.18		10.40		218.50		0.32
CV			16.54		17.32		17.80		17.00		16.78		16.78		17.03
Mean			44.13		0.80		36.73		0.65		38.68		812.3		1.16

^a Grain yield is in tons hectare⁻¹. CV, percentage coefficient of variation; DF, days to flowering; LSD, least significant difference; MS, mean of squares; SS, sum square; Rep, replications; Rep.block, incomplete blocks within replications.

^b $P < 0.001$.

^c $P < 0.05$.

^d $P < 0.01$.

genotypes in Potchefstroom (Table 5). Genotypes with AUDPC < 178.0 were regarded as resistant to BBS, genotypes with AUDPC between 178.0 and 1,137.0 were regarded as moderate resistance, and genotypes with AUDPC > 1,137.0 were regarded as susceptible to BBS disease. As a result, 7.5% of the genotypes exhibited resistance to BBS disease, whereas 54.9 and 37.6% of the genotypes showed moderate and susceptible reaction, respectively. The best local commercial cultivar or the best-performing check had mean BBS severity

rates of 45.0, 45.0, and 5.0%, with grain yields of 1.28, 0.55, and 1.56 t ha⁻¹ in Warden, Middelburg, and Potchefstroom, respectively. The genotypes selected for both traits had mean BBS severity below and a grain yield above the best local commercial cultivar (ADP-0798), with the exception of Potchefstroom, where the genotype selected for both (ADP-0120 and ADP-0079) had approximately the same mean BBS severity and AUDPC as the best local commercial cultivar (ADP-0798).

Table 4. The mean of bacterial brown spot (BBS) severity and grain yield of the 10 best-performing genotypes and the 5 worst-performing genotypes across three sites

Item and ADP ^a	Market class	BBS severity	ADP	Market class	Yield (t ha ⁻¹) ^b
The 10 best-performing genotypes					
ADP-0592^c	Red mottled	15.00	ADP-0097	Brown	1.66
ADP-0790	Red mottled	16.11	ADP-0522	Yellow	1.62
ADP-0432	Red mottled	19.44	ADP-0079	Purple specific	1.59
ADP-0454	Red mottled	21.30	ADP-0122	Cranberry	1.58
ADP-0796	Cranberry	21.30	ADP-0592	Red mottled	1.56
ADP-0126	Navy	22.78	ADP-0545	Cranberry	1.55
ADP-0008	Red mottled	23.15	ADP-0790	Red mottled	1.55
ADP-0125	White	23.15	ADP-0120	Cranberry	1.53
ADP-0079	Purple specific	23.52	ADP-0630	Light red kidney	1.51
ADP-0120	Cranberry	24.63	ADP-0008	Red mottled	1.46
The 5 worst-performing genotypes					
ADP-0391	Red kidney	57.22	ADP-0587	White	0.39
ADP-0609	Dark red kidney	57.22	ADP-0639	Light red kidney	0.38
ADP-0203	Pink	58.33	ADP-0310	Cranberry	0.38
ADP-0652	White kidney	61.30	ADP-0417	Red kidney	0.34
ADP-0310	Cranberry	63.15	ADP-0577	Red mottled	0.32
The best check					
ADP-798 (cultivar Kamiesberg)	Cranberry	31.67	ADP-798	Cranberry	1.13

^a ADP, Andean Diversity Panel lines.

^b Grain yield is in tons hectare⁻¹.

^c Bold indicates high-yielding lines with low disease scores.

Table 5. Mean of bacterial brown spot (BBS) severity, area under disease progress curve (AUDPC; at Potchefstroom), and grain yield of the 10 best-performing genotypes at individual sites

Level of resistance	Warden				Middelburg				Potchefstroom					
	ADP ^a	BBS severity	ADP	Grain yield ^b	ADP	BBS severity	ADP	Grain yield	ADP	BBS severity	ADP	AUDPC	ADP	Grain yield
The most resistant and high yielding	0546	5.00	0546	2.47	0038	8.33	0239	2.13	0120	5.00	0798	105.00	0517	2.31
	0478	15.00	0063	2.31	0551	8.33	0057	2.07	0126	5.00	0797	105.00	0554	2.23
	0376	18.33	0120	2.01	0125	8.33	0621	2.05	0432	5.00	0716	105.00	0522	2.19
	0279	18.33	0473	2.00	0721	8.33	0038	2.03	0716	5.00	0120	105.00	0060	2.17
	0611	18.33	0658	1.99	0592	8.33	0522	2.03	0790	5.00	0790	105.00	0008	2.17
	0355	18.33	0101	1.97	0790	8.33	0192	2.03	0797	5.00	0126	105.00	0120	2.16
	0585	18.33	0673	1.93	0510	8.33	0790	2.03	0798	5.00	0432	105.00	0097	2.15
	0767	18.33	0279	1.91	0093	11.67	0737	1.98	0125	6.11	0125	128.30	0532	2.13
	0120	18.33	0337	1.90	0740	11.67	0721	1.98	0455	6.11	0455	128.30	0527	2.13
	0630	18.33	0630	1.89	0035	11.67	0684	1.94	0079	7.22	0079	151.70	0079	2.12
The least resistant and low yielding	0074	65.00	0730	0.27	0207	68.33	0581	0.19	0587	58.33	0587	1,225.00	0672	0.29
	0203	65.00	0640	0.26	0759	71.67	0481	0.18	0609	58.33	0609	1,225.00	0479	0.29
	0095	68.33	0531	0.24	0770	71.67	0640	0.18	0623	58.33	0623	1,225.00	0598	0.29
	0049	68.33	0078	0.24	0644	71.67	0207	0.18	0598	59.44	0598	1,248.30	0459	0.28
	0640	68.33	0639	0.24	0788	71.67	0595	0.18	0610	59.44	0610	1,248.30	0376	0.28
	0549	71.67	0654	0.24	0659	71.67	0379	0.18	0777	59.44	0777	1,248.30	0280	0.26
	0105	71.67	0681	0.21	0379	71.67	0604	0.18	0220	61.67	0220	1,295.00	0587	0.25
	0797	71.67	0721	0.20	0581	71.97	0765	0.18	0672	61.67	0672	1,295.00	0190	0.23
	0078	71.67	0549	0.20	0652	75.00	0279	0.17	0310	66.11	0310	1,388.30	0279	0.17
	0721	75.00	0746	0.18	0595	75.00	0644	0.17	0733	92.78	0733	1,948.30	0242	0.16
LSD		11.70		0.22		10.48		0.18		10.40		219.00		0.32
Mean		44.13		0.80		36.73		0.64		38.68		812.00		1.16
SE		5.96		0.11		5.34		0.09		5.30		111.00		0.16

^a ADP, Andean Diversity Panel lines; LSD, least significant difference; SE, standard error between predicted means.

^b Grain yield is in tons hectare⁻¹.

Correlation among traits. The correlations among traits at Potchefstroom, namely the relative AUDPC, grain yield (tons hectare⁻¹), DF, and DM, of the 415 ADP dry bean genotypes are presented in Table 6. The AUDPC was highly significant and negatively correlated with grain yield ($r = -0.55$), DF ($r = -0.27$), and DM ($r = -0.47$). Grain yield was highly significant and positively correlated with DF ($r = 0.09$) and DM ($r = 0.33$). DF was highly significant and positively correlated with DM ($r = 0.31$) and grain yield ($r = 0.09$).

Relationship between morphological traits and reaction to BBS disease. The relationship between seed size, growth habit, and reaction to BBS in Potchefstroom is displayed in Figure 1. The genotypes with an indeterminate growth habit showed a lower AUDPC mean than those with a determinate growth habit (Fig. 1A). In addition, the medium-seeded genotypes showed the lower AUDPC mean compared with the large-seeded genotypes (Fig. 1B). Within the indeterminate group, there was no significant difference between large- and medium-seeded genotypes with respect to the AUDPC (Fig. 1C).

Discussion

BBS is an economically important disease to dry bean production globally. This study aimed to identify BBS disease resistance and

Table 6. Correlation between days to flowering (DF), days to maturity (DM), relative area under disease progress curve (AUDPC), and grain yield at Potchefstroom

Traits	DF	DM	AUDPC	Grain yield (t ha ⁻¹)
DF	1			
DM	0.31 ^a	1		
AUDPC	-0.27 ^a	-0.47 ^a	1	
Grain yield (t ha ⁻¹)	0.09 ^a	0.33 ^a	-0.55 ^a	1

^a $P < 0.001$.

high-grain yield performance among 415 ADP dry bean lines and 5 check cultivars. The analysis of variance indicated high variability among selected genotypes for BBS disease resistance and grain yield performance both across and at individual environments.

The study revealed that 17.2% of genotypes were resistant, whereas 45.3% were moderately resistant to BBS disease. These genotypes can be useful sources of genetic resistance for future dry bean improvement for the South African bean market. The high variability among genotypes implies better selection criteria based on resistance and yield performance. The GEI was also significant, which implies rank changes on genotypic performances across different sites. Significant GEI can imply that selection of genotypes is environment specific; hence, genotypes can be selected for a particular environment.

Genotypes ADP-0592, ADP-0790, ADP-0120, and ADP-0008 were selected for both high disease resistance and high grain yield across three environments. Genotypes ADP-0546, ADP-0630, ADP-0120, and ADP-0279 were selected for both high BBS disease resistance as well as high yield in Warden. Genotypes ADP-0038, ADP-0721, and ADP-0790 were the best performing at Middelburg, whereas genotypes ADP-0120 and ADP-0079 were better performing at Potchefstroom. Genotypes selected had the mean grain yield above the grand mean (0.87 t ha⁻¹) and the best-performing cultivar (1.13 t ha⁻¹) and mean BBS severity below the grand mean (39.85) and the best-performing or check cultivar (31.67). These genotypes had either broad or specific adaption with lower mean BBS severity and higher grain yield than the best local commercial cultivar (ADP-0798).

The results indicated that AUDPC was significantly and negatively correlated with grain yield ($r = -0.55$), DF ($r = -0.27$), and DM ($r = -0.47$). The disease occurrence and severity are negatively correlated with maturity period, and the grain yield is negatively correlated with BBS disease severity of the ADP genotypes. The results from the study corroborate with findings by Muedi et al. (2015a, b), who indicated that the higher the AUDPC is, the lower the grain yield will be. The medium-seeded and indeterminate growth habit genotypes had

Fig. 1. Violin plots with boxplots within showing the distribution of reactions to bacterial brown spot disease (area under the disease progress curve) for Andean Diversity Panel bean genotypes grouped by growth habit and seed size. **A**, Distribution of reactions to the disease for genotypes grouped by growth habit, **B**, distribution of reactions to the disease for genotypes grouped by seed size, and **C**, distribution of reactions to the disease for genotypes grouped by seed class within each growth habit type.

lower BBS severity than the large-seeded and determinate growth habit dry bean genotypes. Cichy et al. (2015) indicated that the small-seeded and indeterminate growth habit genotypes were more resistant than large-seeded and determinate growth habit genotypes on study of a dry bean diversity panel for Andean bean improvement. The medium-seeded genotypes had a lower AUDPC mean than the large-seeded dry bean genotypes. Research by Navarro et al. (2007) also reported that the seed size had an effect on resistance to the BBS disease. The genotypes with an indeterminate growth habit had lower disease severity means than those with a determinate growth habit. The suggested reason is that extended vegetative growth in indeterminate genotypes improves plant immunity. These results are similar to what Singh et al. (1991) reported in a study of genetic diversity of cultivated common bean, which included analysis of genotype reaction to common bacterial blight disease.

Several desirable ADP dry bean lines with broad adaptation were identified that had both high grain yield and low BBS disease severity, and these genotypes were regarded as potential sources of both selected traits. These genotypes could be used as donor parents in a breeding program for high yield and resistance to BBS. Four, three, and two genotypes were selected for specific adaptation for Warden, Middelburg, and Potchefstroom, respectively. These genotypes can be recommended for each specific environment. The above genotypes should be further evaluated for two or more seasons and across sites before possible release as commercial cultivars.

The study identified 17.2 and 45.3% of genotypes with resistance or moderate resistance to BBS disease, respectively. Several genotypes were adapted to specific environments. Genotypes ADP-0592, ADP-0790, ADP-0120, and ADP-0008 were selected across the three environments. Genotypes ADP-0546, ADP-0630, ADP-0120, and ADP-0279 were selected for both high BBS disease resistance and high yield at Warden. Genotypes ADP-0038, ADP-0721, and ADP-0790 were the best performers at Middelburg, whereas genotypes ADP-0120 and ADP-0079 were the best performers at Potchefstroom. Genotypes selected had mean grain yield above the grand and the best-performing cultivar, and they had mean BBS severity below the grand mean and the best-performing cultivar. These materials can be used as sources of resistance to BBS in future breeding programs.

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