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Authors
Porch, Timothy
Barrera, Santos
Mier y Teran, Jorge C Berny
et al.

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REGISTRATION

Germplasm

Release of tepary bean TARS-Tep 23 germplasm with broad abiotic stress tolerance and rust and common bacterial blight resistance

Timothy Porch[1] | **Santos Barrera**[2] | **Jorge C. Berny Mier y Teran**[3] | **Jairo Díaz-Ramírez**[4] | **Marcial Pastor-Corrales**[5] | **Paul Gepts**[3] | **Carlos A. Urrea**[2] | **Juan Carlos Rosas**[6]

[1] USDA-ARS, Tropical Agriculture Research Station, Mayagüez, PR 00680, USA

[2] Dep. of Agronomy and Horticulture, Univ. of Nebraska, Lincoln, NE 68583, USA

[3] Dep. of Plant Sciences, Univ. of California, Davis, CA 95616, USA

[4] Desert Research and Extension Center, Univ. of California, Holtville, CA 92250, USA

[5] USDA-ARS, Beltsville Agricultural Research Center, Beltsville, MD 20705, USA

[6] Science and Agricultural Production Dep, Zamorano Univ., Honduras

Correspondence

Timothy Porch, USDA-ARS, Tropical Agriculture Research Station, Mayagüez, PR 00680, USA.

Email: timothy.porch@usda.gov

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Abstract

Tepary bean (*Phaseolus acutifolius* A. Gray) is a drought and high ambient temperature tolerant crop native to the Sonoran Desert, the hottest and driest region in the United States and Mexico. Although tepary bean is an orphan crop with little current commercial production, there was a brief period of larger scale production in the early 1900s in California. Tepary bean has great potential as a novel crop in a warmer world climate and can be introduced as an alternative pulse crop in hot and/or dry regions worldwide. TARS-Tep 23 (Reg. no. GP-309, PI 698457) is an improved tepary bean germplasm with wide-ranging adaptation to tropical and temperate regions experiencing high temperature and drought stress conditions, with broad resistance to bean rust and with resistance to common bacterial blight. It has a flat, mottled black seed type with good seed size, a Type III plant habit, and a short crop cycle of 55–61 d in the environments tested. This germplasm was developed cooperatively by the USDA-ARS, Zamorano University, the University of California–Davis, and the University of Nebraska. The use of this improved germplasm by farmers in production zones affected by abiotic and biotic stresses, or by breeding programs, can potentially increase seed yields of this climate-resilient crop.

1 | INTRODUCTION

Tepary bean (*Phaseolus acutifolius* A. Gray) is the only domesticated *Phaseolus* species with desert adaptation,

Abbreviations: BGYMV, *Bean golden yellow mosaic virus*.

acquired through its evolution in the Sonoran Desert (reviewed by Nabhan & Felger, 1978). As such, it is inherently adapted to high daytime temperatures and drought stress and has great promise for dryland cropping systems and for marginal production zones, especially considering the changing climate. Drought affects more than 60% of common bean (*P. vulgaris* L.) production zones worldwide (White & Singh, 1991), and high temperature stress has become an increasing constraint, with dramatic reductions in production forecast for common bean in Africa (Ramirez-Cabral et al., 2016; Rippke et al., 2016) and worldwide (Palomino, 2012).

High levels of abiotic stress tolerance have been confirmed in cultivated tepary bean through controlled evaluations, including tolerance to heat (Nabhan, 1979; Rainey & Griffiths, 2005), drought (Markhart, 1985), cold (Martinez-Rojo et al., 2007), and salinity (Hendry, 1918; Sternberg et al., 2001). Several studies have begun to describe physiological mechanisms related to its remarkable abiotic stress tolerance including early and deep rooting, small leaf size with effective phototropism, stomatal control, a heat-tolerant photosynthetic apparatus, water use efficiency, and efficient transfer of photosynthates to the grain (Mohamed et al., 2005; Rao et al., 2013; Suárez et al., 2020; Traub et al., 2018). Thus, tepary bean has great potential for dryland cropping systems and marginal production environments.

Further analysis of the adaptation of tepary across temperate and tropical climates is necessary to understand the range of adaptation for the crop in general and for geographical targeting of specific germplasm or cultivars. The impact of elevated day and nighttime temperatures on yield across crops is showing the larger detrimental effects of increases in nighttime versus daytime temperatures (Cox et al., 2020). The complex genotype × environment interaction of daylength, temperature, and genotype in common bean (White & Singh, 1991) is further complicated by the role of vapor pressure deficit in the high-temperature response (Deva et al., 2020; Medina et al., 2017). The response of common bean to variable levels of relative humidity has been shown in the growth chamber environment (Porch & Jahn, 2001). Further investigation of the interactions of temperature, humidity, and daylength will facilitate broader use of tepary bean across climatic zones.

Tepary bean originated from a dry climate somewhat separated from widespread pathogens caused by diseases associated with more humid climates; however, tepary bean accessions have shown resistance to bean rust (Barrera et al., 2020; Miklas & Stavely, 1998), common bacterial blight (Singh & Muñoz, 1999; Urrea et al., 1999), ashy stem blight (Miklas et al., 1998), Fusarium wilt (Miklas et al., 1998), and root rot (Thomas et al., 1983). The bean rust disease, caused by *Uromyces appendiculatus* (Pers.:Pers.) Unger, is a major disease of common bean that also occurs in tepary bean. Broad rust resistance was found in some tepary bean landraces through controlled inoculation with eight individual races of *U. appendiculatus*: 15-1 (41), 15-3 (47), 22-6 (49), unknown (51), 31-1 (53), 31-7 (58), 31-22 (67), and 6-15 (73) (old designations in parentheses) (Miklas & Stavely, 1998). The F_2 populations between resistant and susceptible parents resulted in a 1:2:1 segregation ratio in five landraces, thus suggesting single-gene control of resistance (Miklas & Stavely, 1998). This seemingly simple genetic resistance to rust contrasts with the 13, nine named and four unnamed, resistance genes identified in common bean and points to the importance of screening for additional rust resistance loci in wild tepary bean germplasm (reviewed by Miklas et al., 2006). Tepary bean response to common bacterial blight, caused by *Xanthomonas axonopodis* pv. *phaseoli* (Smith) Dye (Xap), varies widely, but it has the highest levels of resistance within the *Phaseolus* genus (Singh & Muñoz, 1999).

> **Core Ideas**
>
> - TARS-Tep 23 shows heat and drought tolerance in temperate and tropical environments.
> - TARS-Tep 23 has broad rust resistance and common bacterial blight resistance.
> - TARS-Tep 23 shows improved agronomic traits and short maturity.

Published tepary bean improvement efforts began with the release of 'Redfield' tepary selected from Texas landrace T.S. 3306, tested in South Dakota, and released with characteristics including early maturity and high yield (Garver, 1934). The white-seeded TARS-Tep 22 was the first germplasm developed and released through hybridization and modern plant breeding methods and selected for common bacterial blight and rust resistance and abiotic stress tolerance, while TARS-Tep 32 was a selection out of a landrace (Porch et al., 2013).

The goal of this effort was to develop a broadly adapted tepary bean germplasm with high levels of heat and drought tolerance, pyramided with resistance to the bean rust and common bacterial blight diseases, and improved agronomic characteristics. TARS-Tep 23 (Reg. no. GP-309, PI 698457) was developed cooperatively by the USDA-ARS, Zamorano University, the University of California–Davis, and the University of Nebraska.

2 | METHODS

TARS-Tep 23 was derived from the cross of PI 502217-s/PI 440799 completed in 2008 at the USDA-ARS Tropical Agriculture Research Station in a screenhouse in Mayaguez, PR. In 2009, the F_1 generation was planted in the screenhouse. In the winter of 2009–2010, the F_2 was grown at the University of Puerto Rico Experiment Station in Juana Diaz, PR, and single plant selections were completed. The F_3 families were evaluated in 2010 for response to inoculated common bacterial blight and natural powdery mildew, caused by *Erysiphe polygoni* DC, infection under high-temperature conditions in a Mayagüez glasshouse, and single plant selections were again completed. The F_4 plant rows were planted at Juana Diaz under drought stress in the winter of 2010–2011, and superior rows were selected. Seed for continued testing and final release were derived from the F_4 generation.

PI 502217 (syn. G40234) was donated to the USDA-ARS National Plant Germplasm System by the USDA-ARS Cheyenne Horticultural Field Station in Cheyenne, WY. The original collection site for PI 502217 is unknown. PI 502217 is a cultivated tepary bean with large seed size, with resistance to bean rust, common bacterial blight, and powdery mildew, and with good performance in field trials in Puerto Rico (Miklas & Stavely, 1998; Miklas et al., 1994). PI 502217 has a cream speckled seed color. PI 440799 ('Pawi') is a cultivated tepary bean that was collected by Gary Nabhan in 1976 in Chiuli Shaik (Fresnal Village) located at approximately 980 m asl in the Tohono O'odham Nation in Pima County, Arizona. It has a large brown seed type and has performed well in field trials in Puerto Rico.

TARS-Tep 23 was extensively evaluated in field trials from 2011 to 2018 under tropical and temperate climatic conditions and for disease resistance using controlled inoculations for rust and common bacterial blight. Controls used in the trials included a group of cultivated tepary bean accessions tested in Honduras and Puerto Rico. The yellow TARS-Tep 32 and the white TARS-Tep 22 seeded lines were included as checks in these trials and introduced above. A second set of control genotypes were used in the trials in California and Colombia including: G40001 (syn. PI 196932) or 'Frijol Bayo', collected in Veracruz, Mexico, and used for the tepary genome sequence (Moghaddam et al., 2021) with white seed; G40068 (syn. W6 38727), collected in Why, AZ, on the Tohono O'odham Nation with yellow seed; G40111 (syn. W6 38760) or 'Xmayum', collected in Hecelchakan, Campeche, Mexico, with black seed with cream mottling; G40119 (syn. W6 38768), collected in Oaxaca, Mexico, with black seed; G40173A (syn. W6 38814) collected in San Ignacio, Sonora, Mexico, with large yellow seed; G40200 (syn. W6 38855) or 'Ingrato', collected in Carrillo, Guanacaste, Costa Rica, with black seed with cream mottling; and G40284 (syn. PI 485595) or 'Chatchimori' collected in Navajo County, Arizona, with large white seed. Common bean abiotic stress tolerant control genotypes were included in some of the trials in Colombia, California, Honduras, and Puerto Rico including: DOR 390, SEF 10-1, SEF 16, SEF 60, and SEN 52 (all breeding lines from CIAT); 'Verano' (Beaver et al., 2008) and TARS-MST1 (Porch et al., 2012), a cultivar and germplasm, respectively, from Puerto Rico; and 'Zorro' (Kelly et al., 2009), a cultivar from Michigan.

In total, 31 field trials were conducted in California, Colombia, Honduras, and Puerto Rico under a diverse set of climates and soil types and under high-temperature, drought, irrigation, and low-fertility conditions from 2011 to 2018 (Supplemental Table S1). These evaluations were conducted in several tropical, humid environments including on an Inceptisol soil at the Zamorano University, in Zamorano, Honduras, at 805 m asl; on an Inceptisol soil in Nacaome, Honduras, at 44 m asl; on an Andisol soil at Alvarado, Tolima, Colombia, at 418 m asl; on an Entisol soil at Caribia, Magdalena, Colombia, at 18 m asl; and on a Mollisol soil at CIAT in Palmira, Colombia, at 956 m asl. It was also tested in a tropical, humid climate on an Oxisol soil at the USDA-ARS Experiment Station in Isabela, PR, at 125 m asl and in a semiarid tropical climate on a Mollisol soil at the University of Puerto Rico Experiment Station in Juana Diaz, PR, at 28 m asl. Temperate evaluations were conducted on Entisol soils at two University of California experiment stations including the semiarid agricultural experiment station in Davis, CA, at 16 m asl and the arid Desert Research and Extension Center in Holtville, CA, at −22 m asl.

All field trials were planted in a randomized complete block design, with two replications in two trials, three replications in 22 trials, four replications in four trials, and five replications in three trials. Field trials in Puerto Rico were planted in single or two-row, 3-m plots spaced 0.76 m apart; in California experiments were planted in two-row, 3-m plots spaced 1.5 m apart; in Colombia trials were planted in four-row, 3-m plots spaced 0.6 m apart; and in Honduras evaluations were planted in single-row, 3- or 5-m plots spaced 0.7 m apart. All trials were planted, fertilized, maintained, and harvested using standard commercial common bean equipment and methods. High-temperature trials were planted during the high-temperature season and/or at low altitudes, while most drought experiments were planted in side-by-side, drought stress–irrigated trials, and application of water was controlled to induce stress. The drought stress applied across trials was intermittent with irrigation reduced by 50 to 70% between flowering and harvest in the drought stress treatment compared with the irrigated treatment. Agronomic and weather data (Supplemental Table S1) were collected from each trial.

The rust disease inoculations were performed under greenhouse conditions at the USDA-ARS in Beltsville, Maryland with six Mesoamerican races: 13-2 (43), 15-3 (47), 22–6 (49), 31-1 (53), 31-22 (67), and 22–52 (108), and two Andean races: 21-0 (72) and 37-1 (84) of *U. appendiculatus*. The original (old designation) names of the races (in parentheses) were changed following their inoculation on a new internationally accepted set of differential cultivars that included six Andean and six Middle American cultivars, representing the two gene pools of common bean (Steadman et al, 2002). Common bean cultivars were used as controls representing single rust resistance genes, including *Ur-3*, *Ur-4*, *Ur-6*, *Ur-11*, and 'Pinto UI

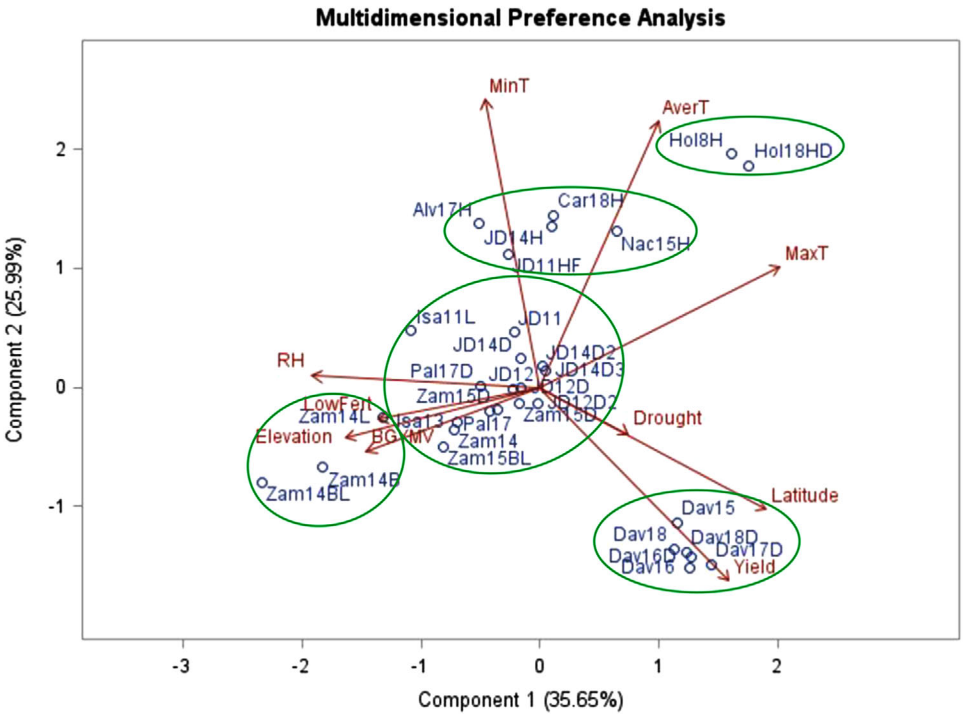

FIGURE 1 Principal component analysis biplot of the linear transformed data for TARS-Tep 23 seed yield (kg ha^{-1}) and characteristics of 31 trials, including elevation (masl); average minimum (MinT), maximum (MaxT), and average (AverT) temperatures (˚C) during the crop cycle; relative humidity (RH); latitude (˚); incidence of *Bean golden yellow mosaic virus* (BGYMV) in TARS-Tep 23 (%); and drought and low fertility (LowFert) binomial indices (0 or 1), for evaluating the grouping of the trials. The trial identifiers start with location including Alv for Alvarado, Colombia; Car for Caribia, Colombia; Dav for Davis, CA; Hol for Holtville, CA; Isa for Isabela, PR; JD for Juana Diaz, PR; Nac for Nacaome, Honduras; Pal for Palmira, Colombia; and Zam for Zamorano, Honduras. The location is followed by a two-digit year identifier for the trial and the final letter indicates the stress, including D for drought; H for high temperature; L for low fertility; F for flooding; B for *Bean golden yellow mosaic virus* disease pressure; or no letter for a non-stress trial

114' as the susceptible check. The inoculum was prepared by suspending urediniospores in a solution of water and Tween 20 for each individual race. Seven days after planting, the primary leaves were inoculated, and the plants were placed in a 100% relative humidity mist chamber at 19 ˚C for 16 h and then transferred to the greenhouse. At 12 d after inoculation, the reaction of each accession and control cultivars was scored using the standard bean rust scale developed by Stavely et al. (1983).

Two common bacterial blight disease evaluations were conducted at the USDA-ARS Tropical Agriculture Research Station in the 2012 summer season in a screenhouse in Mayaguez, PR, and at the University of Nebraska–Lincoln, Panhandle Research Extension Center, Scottsbluff, NE, in the summer of 2020. Common bacterial blight strains 484A and 3353 were inoculated in Puerto Rico and partial results were previously published (Porch et al., 2013). Strain SC4A was inoculated in Nebraska, and both inoculations used the multiple needle technique (Andrus, 1948; Zapata et al., 1985). Natural incidence of ashy stem blight, caused by *Macrophomina phaseolina* (Tasi) Goid. was evaluated in a subset of the 19 trials conducted in Honduras and Puerto Rico using a 1–9 scale, with 1 representing resistance and 9 complete susceptibility (van Schoonhoven & Pastor-Corrales, 1987). *Bean golden yellow mosaic virus* (BGYMV) was present in four trials conducted in Honduras, where susceptible spreader rows increased the inoculum load of this naturally occurring disease, and disease incidence (number of plants with mosaic symptoms) was recorded for each plant row. TARS-Tep 23 was tested for response to the *Bean common mosaic necrosis virus* through inoculation with the NL 3 strain in a greenhouse in Mayaguez, PR, in 2020. Enzyme-linked immunosorbent assay (ELISA) was completed on the leaf samples of the inoculated plants following the Agdia protocol and used to detect the presence of the virus.

The statistical analyses were conducted using the R (R Core Team, 2020) and SAS (SAS Institute) programs. The field data were adjusted for spatial heterogeneity using the SpATs R program of Rodríguez-Álvarez et al. (2018), resulting in a best linear unbiased prediction for each entry in each field trial. This trial mean adjustment for each entry was made to take into account field variability, common in tropical field evaluations, by using the physical column and row location of each plot in each replicate. Fisher's protected

TABLE 1 Yield comparisons of TARS-Tep 23 for 31 trials from 2011 to 2018 in California, Colombia, Honduras, and Puerto Rico presented as spatially adjusted best linear unbiased predictions calculated for each trial. Trial conditions included low fertility (L. fert.), drought, heat, non-stress (NS), and *Bean golden yellow mosaic virus* (BGYMV)

Year	Location	Trial, treatment	Yield												
			TARS-Tep 23	TARS-Tep 22	TARS-Tep 32	G40001	G40068	G40111	G40119	G40173A	G40200	G40284	Exp. Mean	LSD (.05)	CV
			kg ha^{-1}												%
2011	Juana Diaz, PR	1, drought	1,321	1,291	1,195										
2011	Juana Diaz, PR	2, heat, flood	683	417	606										
2011	Isabela, PR	3, L. fert.	565	591	573										
2011	Juana Diaz, PR	4, irrigated	1,433	1,494	1,496										
2011	Juana Diaz, PR	5, drought	893	923	878										
2012	Juana Diaz, PR	6, drought	2,020	1,351	1,692										
2013	Isabela, PR	7, NS	1,370	1,376	939										
2014	Juana Diaz, PR	8, drought	1,127	1,958	1,956										
2014	Juana Diaz, PR	9, heat	1,054	940	1,294										
2014	Juana Diaz, PR	10, drought	1,274	1,268	1,270										
2014	Juana Diaz, PR	11, drought	1,427	1,225	971										
2014	Zamorano, Honduras	12, BGYMV	258	293	224										
2014	Zamorano, Honduras	13, L. fert., BGYMV	175	173	166										
2014	Zamorano, Honduras	14, NS	1,833	1,511	1,691										
2014	Zamorano, Honduras	15, L. fert.	966	828	860										
2015	Zamorano, Honduras	16, L. fert., BGYMV	2,245	2,425	1,484										
2015	Zamorano, Honduras	17, drought, BGYMV	1,175	1,012	856										
2015	Nacaome, Honduras	18, heat	1,272	2,619	2,071										
2015	Zamorano, Honduras	19, drought	2,030	1,996	2,040										
2015	Davis, CA	20, NS	3,080			1,406									
2016	Davis, CA	21, drought	2,882	2,845		1,304	2,358								
2016	Davis, CA	22, NS	3,733	3,148		1,786	2,836								
2017	Alvarado, Colombia	23, heat	1,201	1,294			903	769	948	1,160	1,121	701			
2017	Davis, CA	24, drought	3,905	3,173											
2017	Palmira, Colombia	25, drought	1,027	944		868	1,018	653	793	982	1,003	247			
2017	Palmira, Colombia	26, NS	2,378	2,371			1,937	1,671	1,861	1,901	2,089	584			

(Continues)

TABLE 1 (Continued)

Year	Location	Trial, treatment	Yield												
			TARS-Tep 23	TARS-Tep 22	TARS-Tep 32	G40001	G40068	G40111	G40119	G40173A	G40200	G40284	Exp. Mean	LSD (.05)	CV
2018	Caribia, Colombia	27, heat	993	933		825	516	514	981	767	811	−61			
2018	Davis, CA	28, drought	3,014	2,430		1,403	2,370	164	1,066	2,352	1,197	59			
2018	Davis, CA	29, NS	3,390	2,882		1,357	2,722	76	2,187	2,520	1,600	402			
2018	Holtville, CA	30, heat	1,154	125		697	370	207	668	435	102	83			
2018	Holtville, CA	31, heat, drought	1,041	314		−78	84	135	324	149	156	33			
Mean	31 trials		1,643	1,472									1,559	167	20.5
	19 trials		1,217	1,247	1,172								1,212	174	21.8
	10 trials		2,269	1,777		1,063	1,579						1,688	375	23.1
	8 trials		1,775	1,412			1,240	524	1,104	1,283	1,010	256	1,075	478	44.2
Yield percentage			100	86	68	60	83	31	65	75	59	15			

LSD ($p < .05$) was then used to compare entry means across trials that had significant *F*-tests for entries using SAS. Principal component analysis was conducted using PROC PRINQUAL in SAS to evaluate the interaction between TARS-Tep 23 yield with maximum and minimum average daily temperatures, relative humidity, latitude, elevation, natural incidence of BGYMV, and drought or low-fertility treatments in the trials. *Bean golden yellow mosaic virus* is presented as the average percent incidence of the disease in TARS-Tep 23 plots (Supplemental Table S1). Due to the complexity of comparing drought stress and fertility stress across locations, a binary 0 (non-stress) or 1 (drought or low fertility) designation was assigned to each trial.

3 | CHARACTERISTICS

3.1 | Environments

Of the 31 field trials conducted (Supplemental Table S1), 22 were abiotic stress trials, including 12 drought, 7 high-temperature (with two trials having additional drought or flooding stress), and 4 low soil fertility trials (2 of which had natural BGYMV disease pressure in Honduras). The low soil fertility was primarily due to low N in these trials.

The high-temperature locations were characterized by high average maximum temperatures (daytime) ≥35 ˚C (Nacaome, Honduras), high minimum temperatures (nighttime) ≥24 ˚C (Caribia and Alvarado, Colombia; Juana Diaz, PR), and by both high maximum and minimum temperatures (≥35 and 24 ˚C, respectively; Holtville, CA) based on average ambient temperature conditions during the crop cycle (Supplemental Table S1). This classification of heat stress occurring at temperatures ≥35 ˚C daytime and 24 ˚C nighttime for tepary bean is empirical, based on the results of this study, and is considerably higher than that designated for common bean of >30 ˚C daytime and 20 ˚C nighttime.

Principal component analysis (Figure 1) was conducted based on the environmental variables included in Supplemental Table S1 and on TARS-Tep 23 seed yield response. The clustering of trials was used to classify the trials into the five circled groups of environments, described below, followed by the yield of TARS-Tep 23 in parentheses. These five environments included: the mid-altitude low fertility and/or BGYMV affected trials in Honduras (756 kg ha^{-1}, three trials); the high temperature, lowland, tropical environments of Puerto Rico, Colombia, and Honduras (1,041 kg ha^{-1}, five trials); the dry, very hot (40/24 ˚C day/night), mid-latitude environment of Holtville, CA (1,098 kg ha^{-1}, two trials); the tropical environments with drought and/or other stress in Colombia, Puerto Rico, and Honduras (1,417 kg ha^{-1}, 15 trials); and the dry, warm, mid-latitude environment of Davis, CA (3,334 kg ha^{-1}, six trials). Clearly, the Davis, CA, environ-

TABLE 2 Average yield per day, days to maturity, 100-seed weight, biomass, harvest index (HI), and response to ashy stem blight (ASB) of tepary bean accessions and breeding lines in a group of eight trials conducted in California (four trials) and Colombia (four trials) in 2017–2018 and in a group of 19 trials conducted in Honduras (eight trials) and Puerto Rico (11 trials) from 2011 to 2015 based on spatially adjusted best linear unbiased predictions calculated from each trial

Line	Yield per day		Days to maturity		100-seed weight		Biomass	HI	ASB
	8 trials	19 trials	8 trials	19 trials	8 trials	19 trials	19 trials	19 trials	19 trials
	$kg\ ha^{-1}\ d^{-1}$		d		g		$kg\ ha^{-1}$		1–9[a]
TARS-Tep 23	26.4	18.1	55.2	60.9	13.5	13.9	3,284	0.45	3.3
TARS-Tep 22	25.2	17.9	55.6	63.4	11.2	12.7	2,972	0.40	3.3
TARS-Tep 32		17.1		63.6		15.3	3,041	0.44	3.5
G40068	20.3		55.9		12.2				
G40111	16.3		58.7		12.6				
G40119	19.7		60.8		10.6				
G40173A	21.5		55.8		14.2				
G40200	23.9		54.4		11.0				
G40284	5.9		69.6		13.7				
Mean	20.5	17.7	57.8	62.6	12.4	13.9	3,098	0.43	3.4
LSD (.05)	6.8	2.2	4.2	4.9	2.7	0.8	464	0.04	0.38
CV (5%)	18.2	16.3	4	10.1	21.7	6.4	12.9	8.2	4.9

[a]Response to ashy stem blight (ASB), caused by *Macrophomina phaseolina*, on a 1–9 scale, where 1 = resistant and 9 = susceptible.

ment far exceeded the other testing environments for TARS-Tep 23 seed yield performance, probably the result of the environment more closely reflecting the hot day and cool night, desert-type climate of tepary bean's native Sonoran Desert environment and indicates its high yield potential. The seed yield vector in the first principal component (PC1) is somewhat aligned with the drought vector, suggesting high levels of drought tolerance of TARS-Tep 23 for the conditions under which it was tested. The susceptibility of TARS-Tep 23 to BGYMV, when this virus was present in Honduran trials, resulted in low yields. The seed yield vector direction is relatively opposed to the minimum temperature and relative humidity vectors, indicating that TARS-Tep 23 may be sensitive to the higher nighttime temperatures and relative humidity present in these evaluations or shows poorer adaptation to lowland, high-humidity tropical environments in general. The sensitive reaction to high night temperatures has been found in common bean (Gross & Kigel, 1994) and in crop plants in general (Hatfield et al., 2011), and this is of concern given that nighttime temperatures are increasing at a faster rate with climate change (Cox et al., 2020). However, current common bean production climates are more limited by high daytime than nighttime temperatures (Beebe et al., 2011; Yadav et al., 2011).

3.2 | Performance

TARS-Tep 23 showed broad adaptation across the temperate and tropical trial locations. The average seed yield was 1,643 $kg\ ha^{-1}$ across the 31 trials (Table 1), with 71% of the trials representing some form of abiotic stress. These remarkable seed yields of TARS-Tep 23 under drought, high temperature, and low fertility conditions are promising for production in agricultural zones marginalized by climate change. In the 31 trials, TARS-Tep 23 had a significantly higher yield than TARS-Tep 22, which averaged 1,472 $kg\ ha^{-1}$. In a subset of 10 trials in California and Colombia, TARS-Tep 23 yielded significantly more than the other three tepary lines in the trials with an average seed yield of 2,269 $kg\ ha^{-1}$, while TARS-Tep 22 averaged 1,777 $kg\ ha^{-1}$, G40068 averaged 1,579 $kg\ ha^{-1}$, and G40001 averaged 1,063 $kg\ ha^{-1}$. G40068 was previously found to be a top performing tepary line under drought stress (Rao et al., 2004). In the 19 lowland tropical trials conducted in Puerto Rico and Honduras, TARS-Tep 23 (1,217 $kg\ ha^{-1}$), TARS-Tep 22 (1,247 $kg\ ha^{-1}$), and TARS-Tep 32 (1,172 $kg\ ha^{-1}$) seed yields were quite similar. In a subset of eight trials conducted in California and Colombia with a larger set of tepary lines, TARS-Tep 23 yielded 1,775 $kg\ ha^{-1}$ and TARS-Tep 22 yielded 1,412 $kg\ ha^{-1}$, which were not significantly different. However, TARS-Tep 23 had significantly higher yields than the other six tepary lines in the trials including the next highest yielders G40173A, which averaged 1,283 $kg\ ha^{-1}$ and G40068 that averaged 1,240 $kg\ ha^{-1}$. In two trials representing the most marginal climates, TARS-Tep 23 performed very well with a yield of 1,154 $kg\ ha^{-1}$ under extreme heat (40/24 ˚C, day/night) in Holtville, CA, while the other seven tepary bean lines averaged 284 $kg\ ha^{-1}$. In the same Holtville, CA, extreme heat trial but with additional drought stress, TARS-Tep 23 yielded 1,041 $kg\ ha^{-1}$ while the

FIGURE 2 Uncooked (left) and cooked (right) seed of TARS-Tep 23. The cooked seed was soaked for 12 h and then cooked for 1 h, both in distilled water. The line represents 1 cm

other seven tepary beans averaged 171 kg ha^{-1}. DOR 390 and SEF 60, a common bean heat-tolerant check and an interspecific tepary–common bean hybrid, respectively, yielded 0 kg ha^{-1} (data not shown). For the most part, the common bean heat-tolerant cultivars and lines had uneconomical seed yields (<500 kg ha^{-1}) in the high-temperature trials.

TARS-Tep 23 had a medium 100-seed weight averaging 13.5 g 100^{-1} across eight trials in California and Colombia (Table 2) and 13.9 g 100^{-1} across 19 trials in Honduras and Puerto Rico. It has an acceptable seed quality (Figure 2). A previous study showed some TARS-Tep 23 seed had the hard-shell (Stanley, 1992) or hard-to-cook trait (low water uptake) in seed grown in Isabela, PR, in 2013; however, several common bean lines also showed this trait under the same trial conditions (Porch et al., 2017). Seeds harvested in California did not show this hard-to-cook trait (J.C. Berny Mier y Teran, unpublished data, 2021); however, this trait was not evaluated at other locations. Previously published data also showed that TARS-Tep 23 had promising Fe and Zn composition, with 88 μg g^{-1} dry-weight basis for Fe and 37 μg g^{-1} for Zn from seed harvested in the 2013 Isabela, PR, trial (Porch et al., 2017). Seeds of TARS-Tep 23 showed a slightly flat shape and a light mottled black color, with values of L* = 47.0, chroma = 993.7, and hue = 68.1 using the Hunter Labscan XE Colorimeter, which were quite distinct from the black common bean lines in the 2013 trial (Porch et al., 2017).

TARS-Tep 23 showed an indeterminate bush type III habit under stress (van Schoonhoven & Pastor-Corrales, 1987). It had the highest biomass in the subset of trials conducted in Puerto Rico under heat, drought, and non-stress conditions where biomass was measured, with an average harvest index of 0.45, which was significantly higher than TARS-Tep 22 (0.40) (Table 2). It is important to note that the habit of TARS-Tep 23, and many tepary bean lines, varies depending on the availability of water and fertility. TARS-Tep 23 has a more compact habit and shorter period of days to maturity under drought and fertility stress and a larger, more prostrate habit when sufficient water and fertility are present. Beebe et al. (2008) have suggested that the tendency to revert to a wild

TABLE 3 Response of tepary bean lines and one common bean susceptible cultivar (Pinto UI 114) inoculated with eight races of the rust pathogen including six Mesoamerican races: 13-2 (43), 15-3 (47), 22-6 (49), 31-1 (53), 31-22 (67), and 22-52 (108), and two Andean races: 21-0 (72) and 37-1 (84) of *Uromyces appendiculatus*. The original or old designations of the races (in parentheses) were renamed following their inoculation on a new internationally accepted set of 12 common bean differential cultivars, six Andean and six Middle American (Steadman et al., 2002)

	Mesoamerican races						Andean races	
Line	13-2 (43)	15-3 (47)	22-6 (49)	31-1 (53)	31-22 (67)	22-52 (108)	21-0 (72)	37-1 (84)
TARS-Tep 23		1 (R)	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)
TARS-Tep 22	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)	1 (R)
TARS-Tep 29	4 (S)	4 (S)	4 (S)	4 (S)	4, 5 (S)	5 (S)	f2/3 (TP)	2, f2 (S)
TARS-Tep 32	4 (S)	4, 5 (S)	4, 5 (S)	4 (S)	5, 4 (S)	5, 4 (S)	4 (S)	3 (S)
G 40001	4, 5, 6 (S)	4, 5 (S)	4, 5 (S)	4, 5 (S)	f2, 3 (TP)	f2, 3 (TP)	f2 (TP)	f2, 3 (TP)
Pinto UI 114 (check)	4, 5 (S)	5, 6 (S)	5, 6 (S)	4, 5 (S)	4, 5 (S)	4, 5 (S)	5,6 (S)	5, 6 (S)

Note: The response of the tepary and common bean lines and cultivars to individual races of the bean rust pathogen was evaluated using a standard bean rust grading scale from 1 to 6, where 1 = no visible symptoms; 2+ = necrotic spots, known as hypersensitive reactions (HR), without sporulation, 0.3–1.0 mm in diameter; f2 = tiny faint chlorotic spots without sporulation; 3 = tiny sporulating pustules (TP), <0.3 mm in diameter; 4 = large sporulating pustules, 0.3–0.5 mm in diameter; 5 = large sporulating pustules, 0.5–0.8 mm in diameter; and 6 = large sporulating pustules, >0.8 mm in diameter. All sporulating pustules are the fruiting structures (uredinia) of the rust pathogens. Reactions f2, HR, and 3 were considered resistant (R) and 4, 5, and 6 (large sporulating pustules) were considered susceptible (S).

viny habit under favorable conditions is present in common bean and can be countered by selecting for improved sink strength in the process of breeding. Additional efforts are needed to improve tepary bean architecture for direct combine harvest in humid climates, whereas in more arid climates like California, tepary bean can potentially be mechanically windrowed and harvested with a combine.

TARS-Tep 23 shows potential as an early-maturity, high-yielding germplasm. Mean maturity ranged between 55.2 d in the eight trials in California (latitude 32.8 to 38.5) and Colombia (latitude 3.5) to 60.9 d in the 19 trials conducted in Puerto Rico (latitude 18.0) and Honduras (latitude 14.0) (Table 2). Calculated on a seed yield per day basis, TARS-Tep 23 yielded between 18.1 and 26.4 kg ha^{-1} d^{-1} in the 19 and 8 trials, respectively. This range in seed yield per day under stress is similar to values reported for elite common bean lines under drought and phosphorus stress treatments (Beebe et al., 2008). The development of TARS-Tep 23 illustrates that tepary bean has the potential as a highly productive short-season rotation crop.

3.3 | Disease resistance

TARS-Tep 23 showed broad and high-level resistance to all six Andean and two Mesoamerican races of the bean rust pathogen (Table 3). TARS-Tep 23 and TARS-Tep 22 showed an immune reaction (no visible symptoms) to all eight races of the bean rust pathogen tested in the controlled greenhouse evaluation. Conversely, TARS-29, TARS-32, and the common bean check (Pinto UI 114) were susceptible to all six Mesoamerican races but had a low level of resistance to the 21-0 and 37-1 Andean races. The immune reaction exhibited by TARS-Tep 23 and TARS-Tep 22 is not known to occur in common bean and is a key trait for potential transfer to common bean.

TARS-Tep 23 was resistant to the common bacterial blight pathogen in the screenhouse in Mayaguez, PR, in 2012, with an average rating for the two strains tested of 1.4 on a 1–9 scale (van Schoonhoven & Pastor-Corrales, 1987) and a rating of 9.0 for susceptible check ‘Morales’ and of 1.6 for the resistant check VAX 6 for the two strains (Porch et al., 2013). In Nebraska in 2020, TARS-Tep 23 was resistant in a greenhouse evaluation with a rating of 1.3 for strain SC4A, while the susceptible check cultivar ‘Orion’ had a rating of 8.0. TARS-Tep 23 showed moderate resistance to ashy stem blight in the few trials where it occurred among the 19 trials conducted in Honduras and Puerto Rico (Table 2). TARS-Tep 23 was highly susceptible to natural infection of BGYMV in three trials conducted in Honduras, two of which showed high BGYMV incidence with little seed yield produced. TARS-Tep 23 was susceptible to the NL 3 strain of the *Bean common mosaic necrosis virus*, testing ELISA positive after inoculation.

4 | AVAILABILITY

Seed of this germplasm has been deposited in the USDA-ARS National Plant Germplasm System, where it will be available immediately upon publication for research purposes, including development and commercialization of new cultivars. A limited quantity of seed of the germplasm may be obtained by writing to orders@ars-grin.gov or to the corresponding author (timothy.porch@usda.gov). It is requested that appropriate recognition be made if this germplasm contributes to the development of a new breeding line or cultivar.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Timothy Porch https://orcid.org/0000-0002-5107-2448
Santos Barrera https://orcid.org/0000-0001-6452-4979
Jorge C. Berny Mier y Teran https://orcid.org/0000-0003-3709-9131
Jairo Díaz-Ramírez https://orcid.org/0000-0003-1815-8028
Marcial Pastor-Corrales https://orcid.org/0000-0003-3325-339X
Paul Gepts https://orcid.org/0000-0002-1056-4665
Carlos A. Urrea https://orcid.org/0000-0002-1336-3199
Juan Carlos Rosas https://orcid.org/0000-0003-4396-702X

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