Inheritance of ICA Bunsi-Derived Resistance to White Mold in a Navy × Pinto Bean Cross

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ABSTRACT

Pinto beans (*Phaseolus vulgaris* L.) of cool subtropical and temperate origins are extremely susceptible to white mold disease caused by *Sclerotinia sclerotiorum* (Lib.) de Bary. Breeding pinto beans with resistance to white mold is difficult because of the paucity of resistant germplasm in a closely related background. White mold resistant 'ICA Bunsi', a small white navy bean, is from the same Middle American gene pool, but it is of warm tropical origin and needs to be exploited in pinto bean improvement. Our objectives were to determine inheritance of ICA Bunsi-derived resistance in a cross with pinto bean, determine association of the resistance with disease avoidance, and identify white mold resistant pinto beans. White mold reactions of 85 $F_{5:8}$ recombinant inbred lines (RIL) from the cross 'Aztec'/ND88-106-04 were characterized in the field in North Dakota and Washington in 2001 and 2002. Aztec pinto is susceptible to white mold, and ND88-106-04 navy bean has partial resistance derived from ICA Bunsi. Disease severity score (1 = no disease to 9 = completely susceptible), yield, and disease avoidance traits were measured. Disease severity for Aztec and ND88-106-04 across environments was 6.9 and 2.5, respectively, compared with 4.6 for ICA Bunsi. Reduced lodging and late maturity enhanced disease avoidance. The RILs with stay-green stem at harvest, similar to ND88-106-04, also exhibited less disease. Normal distribution and moderate heritability (H_{ns} = 56 and 36% for WA and ND environments, respectively) for disease score indicated resistance was influenced by environment and likely conditioned by genes with small effects. Nonetheless, white mold resistance was present in a few RILs with high yield potential and pinto seed type.

White mold is a major concern to dry bean growers across the USA (Steadman, 1983). The pinto, small red, pink, and great northern beans from the Durango Race of the Middle American gene pool are very susceptible to white mold disease (Miklas, 2000). A survey of mostly pinto and navy bean growers in North Dakota and Minnesota found white mold as the most serious disease, with fungicides used on 33% of the acreage to control the disease (Lamey et al., 2000). Schwartz and Steadman (1989) reported losses averaging 30% in Nebraska with individual field losses as high as 92%.

White mold is difficult to control in pinto and other dry bean market classes of Race Durango with predominately indeterminate prostrate growth habit (Type III). Application of benzimidazole fungicides is costly but has been the primary method of control. Timing and mode of fungicide applications during the blossom period are critical for good control. Applications also may be hampered by wet weather conditions that favor disease development. Reducing or eliminating late-season irrigation of fields infested with white mold may reduce disease incidence (Steadman et al., 1976). Other cultural practices, such as crop rotation, tillage practices, and reduced seeding rates, recommended to control the pathogen (Zaumeyer and Thomas, 1957) have met with little success (Schwartz and Steadman, 1989).

Genetic resistance and upright and open plant architecture have both been identified as useful mechanisms for reducing white mold damage in dry bean. Fuller et al. (1984) and Lyons et al. (1987) observed that heritability of resistance to white mold in dry bean was low and probably controlled by several genes. Subsequent studies involving different resistance sources have shown heritability of white mold resistance in dry bean to range from low to moderately high (Kolkman and Kelly, 2002: Miklas and Grafton, 1992; Miklas et al., 2001, 2003; Park et al., 2001). The use of avoidance mechanisms, including upright and open plant structure, less dense canopies and branching patterns, elevated pod set, and reduced lodging (Schwartz et al., 1987) have been suggested for reducing white mold damage. These architectural traits enhance penetration of the canopy by sun and aid air circulation, thereby creating a microclimate that is less conducive for infection and disease progression.

Recently, efforts to identify high levels of white mold resistance have intensified, and several resistant snap and dry bean germplasm have been discovered. The Andean cultivars Jatu Rong synonymous with G 122 (Miklas et al., 2001) and PC 50 (Park et al., 2001) and snap bean breeding line NY6020-4 (Miklas et al., 2003) possess major genes (QTL) that condition partial resistance in greenhouse tests and physiological resistance and/or avoidance in the field. However, use of large-seeded Andean and snap bean germplasm for improvement of pinto bean has met with limited success because of the inability to recover a pinto phenotype with acceptable yield potential (Miklas and Grafton, 1992). Virtually no progeny from intergene pool (Andean/Middle American) hybridizations attain the yield potential or commercial phenotype of the Middle American parent (Kornegay et al., 1992; Singh, 1995; Welsh et al., 1995).

Navy bean ICA Bunsi (synonymous with Ex Rico 23) from the tropical race Mesoamerica of the Middle American gene pool is a known source of resistance to white mold (Tu and Beversdorf, 1982). ICA Bunsi resistance was moderate to highly heritable (H_{ns} = 47, 70, and 82%) in three separate navy bean populations (Kolkman and Kelly, 2002; Miklas and Grafton, 1992). ICA Bunsi is high yielding and more closely related to pinto bean than Andean and snap bean cultivars; therefore, it will likely provide more useful pinto bean recombinants

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Abbreviations: H_{ns} = narrow sense heritability; RIL, recombinant inbred line.

with white mold resistance. Furthermore high-yielding progenies are readily obtained from interracial Durango/Mesoamerican populations (Singh et al., 1993). There are no previous reports of the exploitation of ICA Bunsi-derived resistance to white mold in pinto bean. The objectives were to: (i) determine the heritability of ND88-106-04-derived resistance to white mold in pinto bean, (ii) examine the association of resistance with disease avoidance, and (iii) identify pinto bean lines with white mold resistance.

MATERIALS AND METHODS

Eighty-five F_5–derived F_8 RILs, randomly developed from the population Aztec/ND88-106-04, were obtained by the single-seed descent method (Fehr, 1987). Generation advancements were conducted in the greenhouse and in fields free from white mold. Aztec is a semi-upright pinto bean (Kelly et al., 1992) susceptible to white mold. ND88-106-04 from the cross N85007/ICA Bunsi is an upright navy bean breeding line with resistance to white mold putatively derived from ICA Bunsi.

Aztec, ND88-106-04, 85 $F_{5:8}$ RILs, resistant ICA Bunsi, and susceptible pinto check 'Montrose', were evaluated for reaction to white mold in four field environments. The trials were planted 5 June 2001 on a grower's farm at Hatton, ND, 30 May 2002 at the NDSU Experiment Station at Carrington, ND, and 13 June 2001 and 12 June 2002 at the USDA-ARS Cropping Systems Research Farm at Paterson, WA. All three sites have a history of white mold disease in dry bean. Three replications were planted in randomized complete blocks at each location. For the ND trials, a plot consisted of a single row, 3 m long, and bordered on each side by a row of the susceptible 'Othello'. Row spacing for Hatton was 0.76 m and Carrington 0.45 m. Planting density was 147 000 seeds ha^{-1} at Hatton and 245 000 seeds ha^{-1} at Carrington. For the WA trials, a plot consisted of three rows, 3 m long, and spaced 0.56 m apart. Planting density was 235 000 seeds ha^{-1}.

For all trials, weeds were controlled by pre-plant herbicide, mechanical cultivation, and manually. For ND trials supplemental fertilizer was applied for optimum plant growth. Hatton plots relied upon natural precipitation and an overhead mist system was used at Carrington to maintain optimum moisture conditions for white mold development. At Paterson, WA, approximately 6.3 mm of water was applied by overhead center-pivot irrigation on a daily basis from the onset of flowering to late pod-fill. To maintain vigorous plant growth at Paterson, nitrogen was foliar applied by chemigation at a rate of 22 kg ha^{-1} on a weekly basis from the early seedling growth stage (about 18 d after planting-DAP) to mid pod-fill (about 74 DAP).

Each ND plot was inoculated with approximately 75 mL of a solution containing 1×10^4 mL^{-1} ascospores. Apothecia that developed from sclerotia germinated in Petri plates containing potato dextrose agar (PDA) were allowed to release ascospores onto the Petri plate covers. Collected ascospores were diluted to the desired concentration in distilled water. Spores were kept at approximately 10°C until applied at full bloom using a commercial backpack low-pressure sprayer. Inoculations were conducted at least twice to ensure that inoculation occurred at peak bloom for each RIL.

Disease reaction was scored from 1 to 9 based on combined incidence and severity of infection at physiological maturity (defined as 80% of the pods at harvest maturity), where 1 = no diseased plants and 9 = 80-100% diseased plants and/or 60-100% infected tissue (Miklas et al., 2001). For the Paterson, WA trials only the center row was scored. Traits associated with disease avoidance also were measured. Canopy height (cm) was measured at mid-pod fill. Canopy porosity (Deshpande, 1992) also was measured at mid-pod fill and scored from 1 to 5, where 1 = an open canopy with the soil surface between rows completely visible and 5 = completely closed canopy over the furrow with no soil visible. Maturity (d) was recorded as the number of days from planting to physiological maturity. Lodging (1 to 9; where 1 = no lodging and 9 = >90% lodged) and stay-green stem (1 to 5; where 1 = 0–20% green stem and 5 = 80–100% green stem) were scored at physiological maturity. Lodging data was not obtained for the WA 2002 trial, and stay-green stem was only recorded for the ND trials. Plot yield (kg ha^{-1}) and seed weight (g 100 $seeds^{-1}$) also were measured.

Homogenous error mean squares based on Bartlett's tests (Steel and Torrie, 1980) enabled combined analyses of variance across environments to be performed for each trait using PROC GLM (SAS, 1987). The Washington trial data was combined and analyzed separately from the combined North Dakota data because of the distinct differences in plant growth and yield potential between locations. Narrow-sense heritability (H_{ns}) estimates for each trait were based on a progeny mean basis (Fehr, 1987). Frequency distributions of the RIL means for the different traits were tested for normality using the Shapiro and Wilk test statistic W (PROC Univariate, SAS, 1987). A probability of $P < 0.001$ was used to indicate lack of fit.

Simple correlation coefficients were computed between all trait means averaged across environments by PROC CORR (SAS, 1987). The influence of agronomic traits on disease score was modeled by multiple stepwise regression of the trait means averaged across environments by PROC STEPWISE (SAS, 1987). Traits significant at $P < 0.15$ were included in the model.

RESULTS AND DISCUSSION

White mold reaction of the parents was separable. Aztec was susceptible with an average disease score of 6.9 across all four environments, and ND88-106-04 was resistant averaging 2.5. Disease pressure was greater in WA than ND as indicated by higher mean disease scores for the parents, checks, and 85 $F_{5:8}$ RILs (Table 1). ND88-106-04 was more resistant than ICA Bunsi (resistant check), which is consistent with the results from white mold trials conducted in Michigan (Kolkman and Kelly, 2000). ND88-106-04 may have better disease avoidance than ICA Bunsi because it has a more upright plant profile. The level of physiological resistance for ND88-106-04 and ICA Bunsi was similar based on resistance to oxalate in a greenhouse test (Kolkman and Kelly, 2000).

Montrose (susceptible check) was more susceptible than Aztec because it lacks disease avoidance. Montrose has a dense canopy, prostrate growth habit, and was completely lodged. Given yield potential of Montrose and Aztec are nearly equal in trials free of white mold, the yield under severe disease pressure in WA for Montrose was reduced by at least 40% compared with Aztec. Avoidance characteristics of the parents were similar with few exceptions. Aztec had a taller more porous canopy in WA, and ND88-106-04 was later maturing, variable for lodging and had stay-green stem.

Disease avoidance was expressed in the RIL population because increased canopy height and reduced lodging were associated with less white mold (Table 2). Late maturity also was associated with less disease. Increased canopy height and reduced lodging are desirable traits

Table 1. Mean for white mold disease score, canopy porosity and height, lodging, maturity, stay green, yield, and seed weight for parents, checks, select recombinant inbred lines (RILs), and heritability estimates obtained from 85 $F_{5:8}$ RILs from Aztec/ND88-106-04 population evaluated in four field environments in Washington and North Dakota in 2001 and 2002.

		Disease score†		Canopy				Lodging§		Maturity		Stay green¶	Yield		Seed weight	
				Porosity‡		Height										
		WA	ND	WA	ND	WA	ND	WA	ND	WA	ND	ND	WA	ND	WA	ND
						—— cm ——				—— d ——			—— kg ha^{-1} ——		– g 100 seeds^{-1} –	
Parents																
Aztec		7.5	6.2	2.5	3.0	50	32	6.3	6.2	87	94	1.8	3032	2072	36.4	31.6
ND88-106-04		4.2	2.1	4.0	3.4	51	36	7.7	4.8	91	98	3.9	3026	1600	20.4	15.6
Checks																
ICA Bunsi		6.2	3.8	4.1	3.3	51	37	7.0	5.7	94	99	3.8	2964	1835	19.3	15.8
Montrose		8.5	6.3	5.0	4.0	48	26	9.0	8.9	87	96	3.2	1828	2080	35.6	32.2
Select RILs																
AN-37 pinto		4.4	2.2	3.1	1.8	59	39	3.7	4.2	94	95	2.6	3782	2034	37.3	30.0
AN-69 pinto		6.0	2.1	3.8	3.8	56	45	5.3	4.7	94	101	3.8	2979	2356	38.0	31.4
AN-1 white		4.1	3.0	2.3	2.7	44	34	3.7	6.1	88	94	3.2	3395	1682	32.0	28.0
AN-55 white		4.4	2.5	2.5	2.4	49	38	4.3	6.1	91	95	4.7	3258	1724	30.1	27.2
LSD 0.05 (column)		1.0	2.0	0.7	1.0	5	5	1.6	1.7	3	3	1.0	672	485	2.1	2.6
RIL population																
	means	5.8	3.6	3.6	2.9	52	38	6.2	5.8	94	96	3.1	2863	1799	31.0	24.6
	heritability	0.56	0.36	0.84	0.33	0.53	0.40	0.73	0.21	0.80	0.65	0.54	0.35	0.18	0.91	0.75
90% CI	**upper**	0.63	0.50	0.87	0.45	0.62	0.54	0.80	0.41	0.84	0.72	0.64	0.49	0.37	0.93	0.83
	lower	0.42	0.16	0.80	0.17	0.39	0.25	0.58	0.00	0.75	0.56	0.41	0.13	0.00	0.89	0.72

† Disease score, where 1 = no diseased plants and 9 = 80–100% diseased plants and/or 60–100% infected tissue.
‡ Canopy porosity, where 1 = an open canopy with the soil surface between rows completely visible and 5 = completely closed canopy over the furrow with no soil visible.
§ Lodging, where 1 = no lodging and 9 = >90% lodged.
¶ Stay-green stem, where 1 = 0–20% green stem and 5 = 80–100% green stem.

in otherwise high-yielding cultivars, whereas late maturity is not. The consistent association of late maturity with increased resistance contributes to the difficultly of obtaining white mold-resistant cultivars with grower-acceptable harvest maturity. For a white mold test of 27 high yielding genotypes that included resistance sources, late maturity was associated with less disease (Kolkman and Kelly, 2002). Conversely, in one of three environments, late maturity was associated with increased disease severity in two ICA Bunsi/Newport and Huron/Newport navy bean populations (Kolkman and Kelly, 2002). This particular environment in their study was conducive to maximizing yield of the later maturing genotypes, which created denser canopies favorable for disease development.

Because ICA Bunsi-derived resistance is not detected in the greenhouse straw test (Steadman et al., 2001, 2003), and thought to be only partially expressed in the oxalic acid test (Kolkman and Kelly, 2000, 2003) other mechanisms must contribute to its field resistance. A QTL for resistance on linkage group B2 in the ICA Bunsi/Newport, unassociated with either oxalate resistance or disease avoidance traits (Kolkman and Kelly, 2000, 2003), could be conditioned by a unique field resistance mechanism. For the Aztec/ND88-106-04 population, RILs with stay-green stem trait had less disease (Table 2). Plants with stay-green stem at harvest maturity are likely to be physiologically active, thus still engaged in plant defense response. Plants with stay-green stem also are later maturing.

For arid environments in the western USA, stay-green stem helps to protect seed from mechanical damage during combining. For humid climates (North Dakota, Michigan), where seed is less prone to threshing

Table 2. Simple correlation coefficients among white mold disease score and canopy porosity and height, lodging, maturity, stay green, yield, and seed weight means obtained for 85 $F_{5:8}$ RILs from Aztec/ND88-106-04 population evaluated in two Washington and two North Dakota field environments.

	Canopy				Lodging		Maturity		Stay green	Yield		Seed weight	
	Porosity		Height										
	WA	ND	WA	ND	WA	ND	WA	ND	ND	WA	ND	WA	ND
Disease score (1–9)†	−0.36**	ns	−0.43**	−0.42**	0.23*	0.41**	−0.52**	−0.52**	−0.52**	ns	ns	−0.36**	ns
Canopy porosity (1–5)‡			0.64**	ns	0.43**	0.47**	0.92**	0.63**	0.37**	−0.43**	ns	ns	−0.28**
Canopy height, cm					ns	−0.53**	0.66**	0.42**	0.34**	ns	0.24*	ns	ns
Lodging (1–9) §							0.30**	ns	ns	−0.42**	ns	−0.41**	ns
Maturity, d									0.79**	−0.40**	ns	ns	−0.25*
Stay-green stem (1–5)¶											ns		ns
Yield, kg ha^{-1}												ns	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
ns, Nonsignificant.
† Disease score, where 1 = no diseased plants and 9 = 80–100% diseased plants and/or 60–100% infected tissue.
‡ Canopy porosity, where 1 = an open canopy with the soil surface between rows completely visible and 5 = completely closed canopy over the furrow with no soil visible.
§ Lodging, where 1 = no lodging and 9 = >90% lodged.
¶ Stay-green stem, where 1 = 0–20% green stem and 5 = 80–100% green stem.

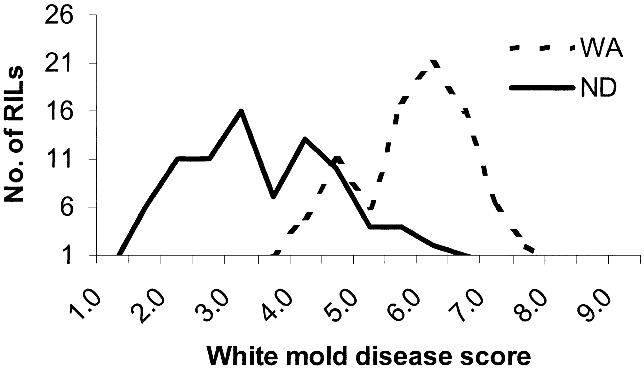

Fig. 1. Frequency distribution of the mean scores (across years) for white mold disease severity reaction (1–9) in the field among 85 RILs (Aztec/ND88-106-04) tested in two separate locations, Washington and North Dakota, in 2001 and 2002 (*W*-tests for normality, $P = 0.03$ in ND and $P = 0.13$ in WA).

damage, stay-green stem is often undesirable because it is associated with delayed maturity, as in this study. Note that Montrose pinto has partial stay-green stem but is completely susceptible. The challenge for breeders will be to develop pinto bean cultivars with partial stay-green stem resistance from ICA Bunsi that are harvestable in humid climates and have acceptable maturity.

The influence of disease avoidance traits such as tall upright plant canopy, stay-green stem, and late maturity on the level of disease incidence and severity is supported by multiple regression analyses. For WA (2001 only), the model [$y = 15.4 - 0.12$ (maturity) $- 0.25$ (porosity) $+ 0.48$ (lodging)] explained 47% of the variation for disease resistance determined by disease score, whereby maturity (26%) and lodging (18%) had the largest effects. For ND, the model [$y = 18.9 - 0.22$ (porosity) $+ 0.39$ (lodging) $- 0.53$ (stay-green stem)] explained 26% of the variation for disease score, whereby stay-green stem (13%) and lodging (12%) had the largest effects. For the ICA Bunsi/Newport population canopy width, canopy height, days to flower and maturity, lodging, branching pattern, and growth habit influenced disease reaction (Kolkman and Kelly, 2002).

The level of white mold severity of the RILs was not associated with yield (Table 2). This lack of a correlation between disease severity and yield is misleading because genotypes with high yield potential have denser canopies with less disease avoidance; therefore, are more prone to white mold infection, thus less able to maximize yield potential. Conversely, lower yield potential genotypes exhibiting disease avoidance from tall and porous canopies and reduced lodging were less prone to white mold infection, thus more able to maximize yield potential. Furthermore, resistant RILs in this study tended to be later maturing with stay-green stem, which translates to less adapted and lower yielding genotypes. There were a few exceptional RILs described below that combined a high level of disease resistance with intermediate maturity and high yield.

Severe white mold pressure reduced seed size in the WA trials (Table 2). Seed size segregated in this population because of the difference in seed size of the parents. Because the small seeded ND88-106-04 is the source of resistance, it is unlikely that there is a genetic association between smaller seed size and white mold susceptibility.

Frequency distribution of the RIL mean disease score was normal for both locations (Fig. 1). The RIL mean disease score was intermediate between the two parents in WA, but slightly skewed toward the resistant parent in ND due to less disease pressure (Table 1). More vigorous plant growth in WA than in ND environments as indicated by taller plant canopies and more lodging contributed to the greater disease pressure in WA.

Yield had the lowest and seed weight the highest heritability estimates (Table 1). Heritability estimates were higher for WA than ND environments due to greater disease pressure, more optimum growing conditions, and less missing data for the WA environments. White mold resistance was moderately heritable (56 and 36%) as were canopy height, lodging, and stay-green stem traits. The normal distribution for disease score combined with low to moderate H_{ns}, and significant genotype × environment interaction in WA (Table 3), indicate that ICA Bunsi-derived white mold resistance is quantitatively inherited, as previously observed (Miklas and Grafton, 1992; Kolkman and Kelly, 2002, 2003).

Table 3. Mean squares for location, genotype, genotype × environment, and error components of variance for white mold disease score and canopy porosity and height, lodging, maturity, stay green, yield, and seed weight for a population of 85 $F_{5:8}$ RILs (Aztec/ND88-106-04) tested across two Washington and two North Dakota field environments in 2001 and 2002.

				Canopy												
		Disease score†		Porosity‡		Height		Lodging§		Maturity		Stay green¶	Yield (10^3)		Seed weight	
Source	df	WA	ND	WA	ND	WA	ND	WA	ND	WA	ND	ND	WA	ND	WA	ND
										d			kg ha^{-1}		g 100 seeds^{-1}	
Environment (E)	1	2.5	5.0*	0.5	3.7*	115*	10 124**		908**	6	21 446**	57**	1 286**	31 078**	185**	775**
Genotype (G)	84	4.6**	7.6**	3.9*	2.3**	158**	60**	3.2**	5.4**	82**	43**	4.5**	132**	26**	127*	66**
G × E	84	1.4**	3.7	0.4	1.2**	50**	24**		3.6**	9*	10**	1.4**	66**	18	6	11**
Error	336 (WA) 296 (ND)††	0.7	2.9	0.4	0.7	18	19	0.9	2.0	7	6	0.8	34	18	5	5

*** Significant (*F*-test) at the 0.05 level of probability.**
**** Significant (*F*-test) at the 0.01 level of probability.**
† Disease score, where 1 = no diseased plants and 9 = 80–100% diseased plants and/or 60–100% infected tissue. Lodging data was obtained in WA in 2001 only.
‡ Canopy porosity, where 1 = an open canopy with the soil surface between rows completely visible and 5 = completely closed canopy over the furrow with no soil visible.
§ Lodging, where 1 = no lodging and 9 = >90% lodged.
¶ Stay-green stem where 1 = 0–20% green stem and 5 = 80–100% green stem.
 # Lodging data was obtained in WA in 2001 only.
†† Less degrees of freedom for the error term reflects missing data for the ND 2002 trial.

Four RILs with high levels of resistance and desirable seed and agronomic traits are highlighted in Table 1. AN-37 and AN-69 have pinto and AN-1 and AN-55 great northern seed type, albeit all four RILs lack desired seed size. These RILs from the Aztec/ND88-106-04 population provide starting germplasm for continued use of ICA Bunsi-derived resistance in pinto and great northern breeding. AN-37 has the same level of resistance as ND88-106-04, but better avoidance characteristics. AN-37 has a more open canopy in ND, increased canopy height, reduced lodging, and less stay-green stem than either the resistant or susceptible parent. Its negative attributes include later maturity in WA and small seed size. The difference in seed size between AN-37 and any standard pinto cultivar is magnified in disease free environments (unreported data). Except for larger seed size, AN-69 is less desirable than AN-37 because of lower yield and later maturity. The seed size and shape of AN-1 and AN-55 are closer to the size and shape of great northern than navy bean. AN-1 has slightly earlier maturity, less stay-green stem, and larger seed size than AN-55, but reduced canopy height.

Significant genetic variation was observed for all of the measured traits (Table 3). Thus, further gains from selection for individual traits such as increased disease resistance, upright architecture, acceptable maturity, or improved yield, should be attainable in larger populations from similar ICA-Bunsi-derived white mold resistant navy bean/pinto bean hybridizations. The difficulty will be to select genotypes with all of the desired traits uniformly expressed across different environments. The significant genotype × environment interactions for each of the desired traits indicates multiyear × location testing will be essential for identifying genotypes that express white mold resistance across different growing conditions.

In summary, navy bean-derived field resistance from ICA Bunsi in Aztec/ND88-106-04) cross was moderately heritable and was introgressed in a few RILs with high yield potential and small pinto and great northern seed type. Use of these RILs should be maximized for obtaining pinto and great northern cultivars with improved white mold resistance.

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