PABLO HENRIQUE TEIXEIRA

IMPROVING INTEGRATED MANAGEMENT OF WHITE MOLD BY USING PARTIAL RESISTANT GENOTYPE AND ADEQUATE PLANT POPULATION IN COMMON BEAN

Thesis submitted to the Plant Sciences Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: José Eustáquio de Souza Carneiro

Co-adviser: Rogério Faria Vieira

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Aos meus pais, Antônio e Marta.

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BIOGRAPHY

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ABSTRACT

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, September, 2022. **Improving integrated management of white mold by using partial resistant genotype and adequate plant population in common bean**. Adviser: José Eustáquio de Souza Carneiro. Co-adviser: Rogério Faria Vieira.

The white mold (WM), caused by the soil fungus *Sclerotinia sclerotiorum*, is the main disease of common bean in the dry season in the Southeastern and Mid-western regions of Brazil. The integrated management by using partially resistant genotypes with adequate plant population may keep WM infection at low damage levels, thereby increasing yield. Studies showed that plant population for beans of type II growth habit could be higher than that currently recommended, but concerns with the possibility of increasing disease, especially WM, lead researchers to limit the plant population recommended. However, as partial resistant genotype of bean may be released soon, the use of high plant population could improve seed yield without a great increase on WM incidence and severity. We conducted two studies. In the first, we reevaluated the strategy of field selections/evaluations in obtaining high-yield genotypes with partial resistance to WM. In the second, we evaluated to the performance of type II bean partially resistant to WM in the field using high plant population in areas infested with sclerotia of *S. sclerotiorum*. In the first study, we assessed four groups (G) of Mesoamerican genotypes and a group of early maturing Andean genotypes (resistant control): G1 = seven genotypes with resistance; G2 = four elite lines with putative resistance; G3 = A195, G122, Cornell 605, and Ouro Branco (Andean), G4 = two cultivars with intermediate resistance, and G5 = three susceptible cultivars. Genotypes of G2 were screened in the 2013-2014 VCU trials; the others, in the 2008-2011 VCU trials. A linear mixed model was used. To evaluate the performance of the type II bean with partial resistant to WM under high plant population, we combined between-row spacing levels (0.25 or 0.50 m) with in-row plant density levels (7, 10, 13 or 16 plants m^{-1}). The effects of these factors on WM infection and yield were assessed using the carioca line CNFC 10720, which has partial resistance to WM. In the first study, the contrast G1,G2 vs. G3 was non-significant for WM incidence and severity index, indicating that genotypes selected for partial resistant were as resistant as the control group. Additionally, G1,G2 yielded 43% more ($p < 0.001$) and produced 33% less sclerotia ($p = 0.001$) than G3. In the second study, yield at 0.25 m was 28% higher than yield at 0.50 m ($p < 0.001$). The use of 13 plants m^{-1} provided the higher yield for both 0.25 and 0.50 m. In conclusion, the first study supports the previous findings and add new evidence that support the effectiveness of the strategy proposed to identify resistance for WM associated with high yield for the dry season in Brazil. The results related to the type II bean with partially resistant to WM indicate that plant population higher than that currently recommended may improve seed yield. However, further studies of plant population are needed under condition of diseases pressure, especially WM, before a conclusion can be reached.

Keywords: *Sclerotinia sclerotiorum*. *Phaseolus vulgaris*. Genetic resistance. Plant population. Dry bean. Escape mechanisms.

RESUMO

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, setembro de 2022. **Melhora do manejo integrado do mofo-branco pelo uso de genótipo parcialmente resistente e população adequada de feijoeiros.** Orientador: José Eustáquio de Souza Carneiro. Coorientador: Rogério Faria Vieira.

O mofo-branco (MB), causado pelo fungo de solo *Sclerotinia sclerotiorum*, é a principal doença nas lavouras de feijão-comum na safra de outono-inverno das regiões Sudeste e Centro-Oeste do Brasil. O uso de genótipos parcialmente resistentes com população de plantas adequada são importantes formas de manejo do MB. Estudos mostraram que a população de plantas para feijoeiros do tipo II poderia ser maior do que a recomendada atualmente, mas preocupações com a possibilidade de aumento de doenças, especialmente MB, limita o uso de alta população. No entanto, como genótipo parcialmente resistente a MB pode ser lançado em breve, o uso de alta população poderia aumentar a produtividade sem um aumento danoso da incidência e severidade de MB. Conduzimos dois estudos. No primeiro, reavaliamos a estratégia de seleções/avaliações em campo para obtenção de genótipos que reúna alta produtividade e resistência parcial ao MB. No segundo, avaliamos em campo infestado com escleródios de *S. sclerotiorum* o desempenho de feijoeiro do tipo II parcialmente resistente ao MB em alta população de plantas. No primeiro estudo, avaliamos quatro grupos (G) de genótipos Mesoamericanos e um grupo de genótipos Andinos de ciclo precoce (controle para resistência) foram avaliados: G1 = sete genótipos com resistência; G = quatro linhagens elites com suposta resistência; G3 = A195, G122, Cornell 605, e Ouro Branco (Andino), G4 = duas cultivares com resistência intermediaria, e G5 = três cultivares suscetíveis. Os genótipos do G2 foram selecionados nos VCUs de 2013-2014; os outros, nos VCU de 2008-2011. Foi usado o modelo linear misto. Para a avaliação do desempenho do feijoeiro do tipo II parcialmente resistente ao MB em alta população de plantas, combinamos espaçamento entre fileiras (0,25 ou 0,50 m) com densidade de plantas (7, 10, 13 ou 16 plantas m^{-1}). Os efeitos desses fatores em doenças e produtividade foram avaliados usando a linhagem carioca CNFC 10720, que tem resistência parcial ao MB. No primeiro estudo, o contraste G1,G2 vs G3 não foi significativo para incidência e índice de severidade de MB, o que indica que genótipos selecionados para resistência parcial ao MB foram tão resistentes quanto o grupo controle. Ademais, G1,G2 alcançou produtividade 43% maior ($p < 0{,}001$) e produziu 33% menos escleródios ($p = 0{,}001$) do que G3. No segundo estudo, a produtividade no espaçamento de 0,25 m foi 28% maior do que 0,50 m ($p < 0{,}001$), e a densidade de 13 plantas m^{-1} foi a mais adequada para ambos os espaçamentos entre fileiras. Como conclusão, os resultados do primeiro estudo suportam conclusões anteriores e acrescenta nova evidência de apoio a eficácia da estratégia proposta para identificar resistência ao MB associada com alta produtividade para a safra de outono-inverno no Brasil. Os resultados relacionados ao feijoeiro do tipo II parcialmente resistente ao MB, indicam que população de plantas maior do que a recomendada atualmente pode melhorar a produtividade de grãos. No entanto, mais estudos de população de plantas sob pressão de doenças, especialmente de MB, são necessários, antes que uma conclusão segura seja obtida.

Palavras-chave: *Sclerotinia sclerotiorum*. *Phaseolus vulgaris*. Resistência genética. População de plantas. Feijão de inverno. Mecanismos de escape.

SUMMARY

GENERAL INTRODUCTION

White mold (WM), caused by soil fungus *Sclerotinia sclerotiorum*, is a serious and difficult disease to control. Chemical control with fungicides is the most used and effective method of WM control (Vieira et al., 2010; Teixeira et al., 2019), but its use alone may be not sufficient to reduce WM. For an effective control of WM, integrated management is needed. Cultural practices as lower plant population, less use of irrigation and nitrogen fertilizer and use of genotype with partial resistance also contribute for reducing this disease (Lima et al, 2019; 2020; Miklas et al., 2013; Schwartz and Singh, 2013).

The partial resistance to WM involves both avoidance and physiological mechanisms. Avoidance, which is expressed under field conditions together with physiological mechanisms, involves phenological and architecture traits. Late maturing genotypes, tall plants with upright growth habit, porous canopy, and resistance to lodging help decreasing WM intensity in bean (Miklas et al., 2013; Schwartz and Singh, 2013; Lima et al. 2020). Physiological mechanisms, which is generally assessed in greenhouse using the straw test (Petzoldt and Dickson, 1996). In previous study, Lima et al. (2020) selected 13 genotypes with putative partial resistant to WM from 14 VCU (preliminary) field trials from 2008 to 2011 in the fall-winter season in Brazil. After that, the selected genotypes for WM resistance were tested with another 6 cultivars (3 screened for susceptibility and 3 screened for intermediate resistant) and the control A195, in six advanced trials. These authors suggested: (i) the partial resistance of the Mesoamerican genotypes to WM are based mainly on avoidance mechanisms; (ii) field trials under WM pressure may provide low cost and fast way to identified high-yielding bean genotypes with partial resistance to WM for the fall-winter season in Brazil. However, there are some methodology limitations on this study: (i) the use of only one resistant control (A195); (ii) the use of ordinal scale instead of an interval or ration scale for the evaluation of the WM; and (iii) the presence of significant and negative WM rating and yield correlation in only two of the six advanced trials. Hence, more planned studies are needed to consolidate our understanding on the screening of beans for partial resistance to WM in the fall-winter season in Brazil and how to evaluate the selected beans.

Currently, in Brazil, many of the released common bean cultivars are type II growth habit, which facilitate mechanical harvesting (Ramalho et al., 2016). In addition, type II cultivars are characterized for tall plants, narrow and porous canopy, reduced branching and pods spread along the stem. These plant characteristics are generally responsible for reducing lodging at harvest, characteristics that disfavor WM (Miklas et al., 2013). The currently recommendation for type II growth habit of common bean is 0.40-0.50 m between-row spacing (BRS) with 11-13 plants m^{-1} (Ramalho et al., 2014) for areas free of *S. sclerotiorum*. Studies suggest that narrower BRS and/or high plant density (PD) may increase the yield of the type II growth habit cultivars (Park et al., 1993; Saindon et al., 1993, 1995; Shimada et al., 2000; Silva et al., 2008; Ziviani et al., 2009), but high plant population is avoided because it may increase diseases, especially WM. We hypothesized that the risk of seed yield reduction due to WM under high plant population is reduced when a partially resistant type II genotype to WM is used.

The objectives of this study were: (i) reevaluate the strategy of field selections/evaluations in obtaining high-yield genotypes with partial resistance to WM; and (ii) evaluate the performance of type II bean partially resistant to WM in the field using high plant population.

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Teixeira PH, Lima RC, Bonicontro BF, Mendes OL, Soares BA, Carneiro JES, Paula Júnior TJ, Vieira R. Management of white mold in common bean using partial resistance and fungicide applications, **Crop Protection**. 2019;124, 104867.

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CHAPTER 1

ASSESSING THE STRATEGY TO IDENTIFY GENOTYPES WITH PARTIAL RESISTANCE TO WHITE MOLD FOR IRRIGATED COMMON BEAN IN BRAZIL USING AN IMPROVED METHODOLOGY

VIÇOSA - MINAS GERAIS
2022

ABSTRACT

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, September, 2022. **Assessing the strategy to identify genotypes with partial resistance to white mold for irrigated common bean in Brazil using an improved methodology**. Adviser: José Eustáquio de Souza Carneiro. Co-adviser: Rogério Faria Vieira.

In previous study, common bean lines/cultivars (genotypes) were selected for reactions to white mold (WM) in the Value for Cultivation and Use trials. These genotypes were then evaluated in field and greenhouse using line A195 as a partial resistant control. It was concluded that field trials were effective in identifying WM-resistant and high-yield genotypes for the dry season in Brazil. Here, we aimed to reassess this strategy using new methodology and new data. Genotypes previously selected and four new lines selected for resistance were used. To evaluate these genotypes, six sprinkler-irrigated trials were conducted using 20 genotypes that formed four groups (G) of small-seeded or a group of large-seeded (control): G1 = seven previously selected and tested for resistance; G2 = four new lines selected for resistance; G3 = A195, G122, Cornell605, and Ouro Branco (partially resistant control), G4 = two with WM reaction between resistant and susceptible, and G5 = three susceptible. A linear mixed model was used. WM was absent or pressure was low/moderate (two trials) or moderate/high (three trials). The contrast G1,G2 vs. G3 was non-significant for incidence and severity index, indicating that genotypes selected for partial resistant were as resistant as the control. Additionally, the genotypes selected for resistance yielded 43% more ($p < 0.001$) and produced 33% lower weight of sclerotia ($p = 0.001$) than the control. In conclusion, the strategy of selection/evaluation of genotypes in the field for WM-resistance confirms its effectiveness in identifying high-yield bean genotypes for the dry season in Brazil.

Keywords: *Sclerotinia sclerotiorum*. Stem rot. Plant density

RESUMO

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, setembro de 2022. **Avaliação da estratégia para identificar genótipos com resistência parcial ao mofo-branco em feijões irrigados no Brasil usando uma metodologia melhorada.** Orientador: José Eustáquio de Souza Carneiro. Coorientador: Rogério Faria Vieira.

Em estudo anterior, linhagens/cultivares (genótipos) foram selecionadas para diferentes reações ao mofo-branco (MB) em ensaios de Valor de Cultivo e Uso (VCU). Depois esses genótipos foram avaliados em campo e casa de vegetação usando a linhagem A195 como controle para resistência. Concluiu-se que ensaios de campo foram eficazes na identificação de genótipos com alta produtividade e resistência parcial ao MB para a safra de outono-inverno no Brasil. Neste trabalho, nosso objetivo foi reavaliar essa estratégia usando nova metodologia e novos dados. Genótipos selecionados anteriormente e quatro novas linhagens selecionadas para resistência foram usados. Para avaliar esses genótipos, seis ensaios irrigados por aspersão foram conduzidos usando 20 genótipos que formaram quatro grupos (G) de mesoamericanos e um grupo andino (controle para resistência): G1 = sete selecionados anteriormente e testados para resistência; G2 = quatro novas linhagens selecionadas para resistência; G3 = A195, G122, Cornell605, e Ouro Branco (controle parcialmente resistente); G4 = dois com resistência intermediária (entre resistente e suscetível) ao MB, e G5 = três suscetíveis. Um modelo linear misto foi usado. A pressão de MB foi ausente ou esteve entre baixa/moderada (dois ensaios) ou moderada/alta (três ensaios). O contraste G1,G2 vs. G3 não foi significativo para incidência e índice de severidade, indicando que os genótipos selecionados para resistência parcial foram tão resistentes quanto ao controle. Ademais, os genótipos selecionados para resistência atingiram produtividade 43% maior ($p < 0.001$) e produziram 33% menos escleródios ($p = 0.001$) do que o controle. Concluiu-se que a estratégia de seleção/avaliação de genótipos em campo para resistência parcial ao MB confirma sua eficácia na identificação de genótipos de feijão-comum com alta produtividade para o outono-inverno no Brasil.

Palavras-chave: *Sclerotinia sclerotiorum*. Podridão da haste. Densidade de plantas

1. Introduction

Approximately 29% of the 2.37 million t of common bean (*Phaseolus vulgaris* L.) produced in Brazil in 2022 were from the fall-winter season (CONAB 2022), which will be called "dry season" from now on. Most of the bean produced in the dry season are from the Southeastern and Mid-western regions of Brazil. In the dry season, rains are scarce, especially during the winter, thereby irrigation is mandatory. In this season, sprinkler irrigation associated with mild temperatures and good conditions for plant growth favor white mold (WM), disease caused by the fungus *Sclerotinia sclerotiorum* (Lib.) de Bary.

Bean resistance to WM is partial and involves both avoidance and physiological mechanisms. Avoidance mechanism, which is expressed under field conditions together with physiological resistance, has been associated with plant architectural and phenological traits (Miklas et al. 2013; Lima et al. 2020) that influence the micro-environment of the host-pathogen interaction (Robison et al. 2018). Architectural traits as tall and porous canopies with lodging resistance help decreasing WM infection in bean (Schwartz and Singh, 2013; Lima et al. 2020). In the dry season in Brazil, the phenological trait late flowering also appear to be an avoidance mechanism (Lima et al. 2020). Physiological mechanisms, which involve biochemical and physical responses to the pathogen (Robison et al. 2018), are generally assessed in greenhouse using the straw test (Petzoldt and Dickson, 1996).

Before the release of an improved cultivar in Brazil, elite breeding lines from different breeding programs are evaluated in the "Value for Cultivation and Use" (VCU) trials. In the VCU trials, the performance of the breeding lines has been compared to the performance of the most-successful cultivars, especially in terms of resistance to foliar diseases and seed yield. Most of the small-seeded cultivar released regularly are from the carioca market class (cream-striped), followed by the black beans.

Lima et al. (2020) selected breeding lines/cultivars (genotypes) of bean for susceptibility, intermediate (between susceptible and partial resistant), and partial resistant to WM in 14 VCU trials conducted from 2008 to 2011 during the dry season in Brazil. Most of these beans were small-seeded genotypes. After that, 19 selected genotypes (13 with putative partial resistance, three with intermediate resistance, and three with susceptibility) and the large-seeded line A195 (resistant control) were evaluated in six advanced field trials. In the advanced trials, some small-seeded genotypes selected for partial resistant to WM had similar WM infection than A195. Additionally, on the average of six trials five small-seeded lines selected for WM-resistance yielded 19% more than A195. The 20 genotypes tested were also assessed in the straw test, in which A195 and Ouro Branco (large-seeded cultivars) had the lowest WM ratings, whereas the small-seeded genotypes that stood out for partial resistance and seed yield in the field trials were among the most susceptible. Therefore, Lima et al. (2020) suggested that the partial resistance to WM of the small-seeded genotypes is based mainly on avoidance mechanisms. These authors concluded that field trials (for selection and evaluation of genotypes) under WM pressure may provide low cost and fast way to identified high-yielding bean genotypes with partial resistance to WM for the dry season.

In one of the advanced trials conducted by Lima et al (2020), A195 had a WM rating of 6.5 (on a 1-9 scale), which is a high rate compared with the ratings obtained by A195 previously (Terán and Singh 2010; Balasubramanian et al. 2014; Lehner et al. 2015). Hence, the authors suggested the inclusion of other sources of physiological resistance in further studies in addition to A195 to improve the methodology to assess partial resistance to WM. Other limitations of the study of Lima et al. (2020) regarding the advanced field trials were: (i) the use of ordinal scale instead of a ratio scale for the WM evaluation, (ii) the presence of significant and negative WM rating and seed yield correlation in only two of the six advanced trials, and (iii) the statistical comparison within genotypes instead of a comparison among groups of genotypes with similar reaction to WM. Hence, more well-design studies are needed to challenge the conclusion of Lima et al. (2020).

Here, we conducted two VCU trials to select genotypes with partial resistance to WM. After that, six advanced trials were conducted with an improved methodology to evaluate the genotypes selected since 2008 (included those selected in two new VCU trials). The improved methodology used in the advanced trials encompasses: (i) using three known WM-resistant controls instead of just one; (ii) evaluating individual plants in each plot for incidence and severity index instead of using visual scale of 1 to 9; and (iii) grouping genotypes with similar characteristics for reactions to WM and determining significant differences among groups of genotypes using orthogonal contrasts. We also evaluated the influence of the rainfall events and genotypes' phenology on WM infection

2. Material and methods

2.1. Genotypes selected for partial resistance to white mold in the 2013 and 2014 preliminary trials

Two VCU trials were established in soils naturally infested with sclerotia of *S. sclerotiorum* in Coimbra (20°49’45” S; 42°45’47” W, 717 a.s.l.), Zona da Mata region, state of Minas Gerais, Brazil, to select bean genotypes with partial resistance to WM. In both trials, the same 25 small-seeded genotypes of the carioca market class of either type II or type III growth habit were used. The trials were established in the dry season: 8 May 2013 and 30 April 2014. The criteria used for the genotype selection for partial resistance was high mean seed yield (main criteria), low WM rating, and resistance to lodging. Light grain color, which consumer associated to quick-cooking beans, was also used as criteria when genotypes exhibited similarity in the other traits. A randomized complete block design with three replications was used. Soil preparation, plot size, fertilization, sprinkler irrigation management and cultural practices were the same described by Lima et al. (2020).

At harvest, lodging and WM rating were evaluated visually on a 1-9 scale (Lima et al., 2020). WM pressure in the trials was considered low when genotypes had median WM rating ≤ 2.0; low/moderate from 2.1 to 3.0; moderate, from 3.1 to 4.0; moderate/high, from 4.1 to 5.0; high, from 5.1 to 6.0; and very high ≥ 6.1. Seeds with 13% moisture harvested from an area of 4 m^2 were used to estimated seed yield.

2.2. Evaluation of genotypes screened between 2008 and 2014 in the advanced field trials

Six advanced field trials were conducted in the dry season in an area with history of white mold to evaluate common bean genotypes selected for different reactions to WM. Each year, one advanced trial was carried out in Viçosa (20°45'14"S, 42°52'55"W, 648 m a.s.l.) and one in Oratórios (20°25'5"S, 42°47'28"W, 492 m a.s.l.), Zona da Mata region, state of Minas Gerais, Brazil. Phenological data and some soil characteristics of the sites used are presented in Table 1.

Table 1 Phenological data of common bean genotypes used in the advanced field trials and soil characteristics of the experimental sites in two districts

District	Year	Sowing date	Data in which 50% of plants reach flowering [a]	Harvest data[a]	Soil characteristic			
					pH $_{H20}$ $_{(1:2.5)}$	Clay (%)	Silt (%)	Sand (%)
Viçosa	2015	16 April	22 May to 4 June	18 to 24 July	5.9	53	24	23
	2016	2 May	7 to 20 June	9 to 18 Aug.				
	2017	24 April	1 to 14 June	1 to 9 Aug.				
Oratórios	2015	2 June	11 to 28 July	1 to 9 Sep.	6.2	31	44	25
	2016	28 April	3 to 14 June	1 to 12 Aug.				
	2017	5 May	11 to 24 June	9 to 16 Aug.				

[a] G122 was the first genotype to reach 50% flowering. Three to five days later plants of the other large-seeded genotypes reached 50% flowering. The earliest small-seeded genotypes (Ouro Negro and Ouro Vermelho) began flowering two to five days after all the large-seeded genotypes have reached 50% flowering.

Six genotypes that exhibited relatively low yield in the study of Lima et al. (2020) were replaced by four lines selected for partial resistance in the 2013 and 2014 VCU trials of the present study and by the genotypes G122 and Cornell605, which are known for their partial resistance to WM. These two genotypes as well as line A195 were used as resistant controls. A195 and G122 (Singh et al. 2007; Pascual et al. 2010; Schwartz and Singh 2013; Balasubramanian et al. 2014; Singh e al. 2014; Lehner et al. 2015; Robison et al. 2018) and Cornell605 (Griffiths 2009; Lehner et al. 2015) exhibit partial resistance to WM in both field and greenhouse (straw test). Seeds from these three genotypes were supplied by S. McCoy (University of Nebraska). Ouro Branco also exhibited both physiological and field resistance (Lima et al., 2020). For this reason, Ouro Branco was also included as resistant control. Ouro Branco, A195, G122, and Cornell605 are large-seeded genotypes with determinate bush type I growth habit and early maturation. In total, 20 genotypes were evaluated.

Five groups (G) of genotypes were formed based on different reactions to WM and period of selection: G1 = seven small-seeded genotypes selected for resistance in the 2008-2011 VCU trials and evaluated in both the 2012-2014 advanced trials and the straw tests using A195 as a partial resistant control; G2 = four small-seeded lines selected for partial resistance in the 2013 and 2014 VCU field trials of the present study; G3 = four large-seeded genotypes with both field and physiological resistance to WM (partially resistant control), G4 = two small-seeded cultivars with intermediate resistance (between partial resistant and susceptible) selected in the 2008-2011 VCU trials and evaluated in both the 2012-2014 advanced trials and the straw tests using A195 as a partial resistant control, and G5 = three small-seeded cultivars with WM-susceptibility selected in the 2008-2011 VCU trials and evaluated in both the 2012-2014 advanced trials and the straw tests using A195 as a partial resistant control (Table 2). The Mesoamerican genotypes (G1, G2, G3, and G4) have indeterminate bush (type II) growth habit, except for the indeterminate type III cultivars Ouro Negro, Ouro Vermelho (prostrate plants), Majestoso, Pérola, VC17, and Vereda (semiprostrate plants).

Table 2 Genotypes forming each group (G) of common bean evaluated in six advanced field trials in the state of Minas Gerais, Brazil

Group (G)	Genotype (market class[a])	Description (levels of resistance to white mold and years of selection)
G1	CNFC10432 (Ca)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	CNFC10720 (Ca)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	CNFC10722 (Ca)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	CNFP10798 (B)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	CNFP11990 (B)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	Vereda (P)	Selected for partial resistance in the 2008-2011 VCU trials[b]
	VC17 (Ca)	Selected for partial resistance in the 2008-2011 VCU trials[b]
G2	VC26 (Ca)	Selected for partial resistance in the 2013-2014 VCU trials
	VC27 (Ca)	Selected for partial resistance in the 2013-2014 VCU trials
	CNFC11946 (Ca)	Selected for partial resistance in the 2013-2014 VCU trials
	CNFCMG-11-06 (Ca)	Selected for partial resistance in the 2013-2014 VCU trials
G3	Ouro Branco (W)	Partially resistant control (selected in the 2008-2011 VCU trials)[b,c]
	A195 (Cr)	Partially resistant control[c]
	G122 (Cb)	Partially resistant control[c]
	Cornell605 (R)	Partially resistant control[c]
G4	Estilo (Ca)	Selected for intermediate resistance in the 2008-2011 VCU trials[b]
	Pérola (Ca)	Selected for intermediate resistance in the 2008-2011 VCU trials[b]
G5	Ouro Vermelho (R)	Selected for susceptibility in the 2008-2011 VCU trials[b]
	Majestoso (Ca)	Selected for susceptibility in the 2008-2011 VCU trials[b]
	Ouro Negro (B)	Selected for susceptibility in the 2008-2011 VCU trials[b]

[a] Ca = carioca (cream-striped), B = black, P = pink, W = white, Cr = cream, Cb = cranberry, R = red.

[b] These genotypes were also evaluated in both the 2012-2014 advanced trials and the straw tests using A195 as a partial resistant control (Lima et al. 2020).

[c] Large-seeded genotypes: A195, G122 and Cornell605 are well-known source of partial resistance to white mold. Ouro Branco was selected as partially resistant and further exhibited both field and physiological resistances.

A randomized complete block design with four replications was used. Each plot had two 3 m-long rows, spaced 0.50 m apart. To avoid a border effect, one border row of the intermediate resistant cultivar Pérola was planted at each side of the trials. Plant density, sprinkler irrigation management, and cultural practices were the same described by Lima et al. (2020) for the advanced trials. In each trial, WM pressure was considered low when the mean of the susceptible cultivars (Majestoso, Ouro Vermelho, and Ouro Negro) exhibited WMI ≤ 25% or WMSI ≤ 15%; low/moderate, 26-45% of WMI or 16-30% of WMSI; moderate, 46-65% of WMI or 31-45% of WMSI; moderate/high, 66-85% of WMI or 46-60% of WMSI; and high, > 85% of WMI or > 60% of WMSI (adapted from Lima et al. 2019).

The following variables were evaluated: days from emergence to flowering and harvesting; canopy closure and height at R7 growth stage (pod filling); lodging, WM incidence (WMI) and severity index (WMSI) at harvest, seed yield, and weight of sclerotia. Canopy closure, canopy height, lodging, and seed yield were evaluated as described by Lima et al. (2020). For canopy closure, 100% represented complete soil coverage by foliage. Grain yield was estimated in 3 m^2. WMSI was evaluated according to methodology described by Kolkman and Kelly (2002), in which:

$$\mathrm{WMSI} = \frac{\Sigma(\text{score assigned to each plant})}{4 \times \ (\text{total number of assessed plants})} \times \ 100$$

In the 2016 and 2017 trials, sclerotia collected on soil surface after harvest + sclerotia mixed with seeds after plant threshing were used to calculate the weight of sclerotia produced by the plants in each plot as described by Teixeira et al. (2019).

2.3. Data analysis

For each VCU trial, seed yield was analyzed by one-way ANOVA, and medians were calculated for each genotype for either WM rating or lodging, which are ordinal data. When genotype affected yield significantly, the means were separated using Fisher's LSD test at $p \leq 0.05$. Spearman correlation was used to establish the relationship between WM rating and seed yield.

Data from the advanced trials were checked for homogeneity of variance (Levene's test) and for normality (Lilliefors's test). Data of canopy height, canopy closure, and weight of sclerotia were transformed by using the Box-Cox Optimal Power method because assumptions were not met. We also graphically assessed the fitted model assumptions by plotting the residuals against the fitted values of each dependent variable. However, untransformed data were presented as mean ± SE. Canopy height, canopy closure, grain yield, and weight of sclerotia were analyzed using linear mixed models with the lmer function. WMI and WMSI, however, were analyzed with the glmer function, because our data had non-normally distributed errors. The fixed effect was groups of genotypes. The random effects were trials and blocks nested within trials. Linear mixed models were analyzed in the lme4 package (Bates et al., 2015) with p-values of fixed effects obtained in the lmerTest package (Kuznetsova et al., 2017) and in the car package (Fox and Weisberg, 2019). When the model showed significance within groups of genotypes ($p \leq 0.05$) for a particular variable, we tested four orthogonal contrasts of interest, using the emmeans function in the emmeans package (Lenth, 2021). Spearman correlation was used to evaluate the relationship between WMSI and seed yield for each trial where WM was observed. Lodging data for each group of genotypes were presented as box-plot graphic. The statistical analysis was performed using R version 4.2.0 (R Core Team, 2022).

3. Results

3.1. Genotypes selected for partial resistance to white mold in the 2013 and 2014 VCU trials

In both trials WM pressure in the fields was high, and genotype affected yield significantly (Table 3). Correlations between WM rating and seed yield were negative and either moderate or high in magnitude. Lines VC27, VC26, CNFC11946 and CNFCMG-11-06 were selected for partial resistance to WM as they exhibited relatively high yield, low WM rating, and some resistance to lodging (Table S1). CNFCMG-11-06 was also selected due to the light grain color.

Table 3 White mold (WM) rating, seed yield, Spearman's correlation coefficient (r) between WM rating and seed yield, and coefficient of variation (CV) for two VCU trials

Trial installation	WM pressure[a]	Range of WM rating[b]	Yield range (kg ha^{-1})	F genotype for yield[c]	r[c]	CV (%)
8 May 2013	high	3.0-8.0	1663-3188	3.64***	- 0.54***	17
30 April 2014	high	3.0-8.0	1183-3477	4.55***	- 0.68***	18

[a] High = median of WM rating for genotypes varied from 5.1 to 6.0 (1 to 9 scale).

[b] Median for genotype using 1 to 9 scale, in which 1 = no diseased plants and 9 = 100% of infected tissues (Miklas et al., 2001).

[c] *** = $p < 0.001$.

3.2. Evaluation of genotypes screened between 2008 and 2014 in the advanced field trials

WM symptoms were absent in Oratórios (2015); low/moderate in Viçosa (2015) and Oratórios (2016); and moderate/high in Viçosa (2016) and in Oratórios and Viçosa (2017). Plants of the genotypes VC17 and Pérola exhibited either moderate/high (2015) or moderate (2017) severity of anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magnus) Briosi Cav.]. Anthracnose impaired evaluations of the variables related to WM, and probably reduced seed yield of these genotypes in higher magnitude than the other genotypes infected only by *S. sclerotiorum* in 2017 and in Viçosa (2015). Thus, these genotypes were excluded from the groups G1 (VC17) and G4 (Pérola) for the mean estimation of the WM variables and yield. However, results of VC17 and Pérola were used for mean estimation of canopy height and canopy closure because these variables were probably only slightly affected by the anthracnose at the time of the evaluation. An increased WMSI was associated with reduced yield in two trials: Viçosa (2016) (r = -0.54, $p < 0.001$) and Oratórios (2017) (r = -0.42, $p < 0.001$).

The means of canopy height for each group of genotypes ranged from 43.7 (G3) to 52.0 (G1) cm (Fig. 1a); the means of canopy closure ranged from 75.1% (G3) to 88.8% (G5) (Fig. 1b). Plants of the G5 clearly exhibited the greatest lodging at harvest (Fig. 2). The mean of canopy height for the three groups associated with partial resistance (G1, G2 and G3) was 6.0% higher than the mean for both G4 and G5 (contrast G1-G3 vs. G4,G5, Table 4). In addition, the mean of canopy closure was 3.3 percentage points lower for G1-G3 in comparison with the mean for the groups with intermediate resistance and susceptibility to WM. The putative resistant groups (G1 and G2) had canopy 18% taller and a canopy closure 11 percentage points greater than those for the G3 (resistant control). The means of these canopy variables for the genotypes selected for resistance in the 2008-2011 VCU trials and further evaluated in field and greenhouse using A195 as a partial resistant control (G1) did not differ significantly from the means for the genotypes selected for resistance in the 2013 and 2014 VCU trials (G2). Canopy for the intermediate resistant group (G4) was 10% taller and 5.9 percentage points more open than canopy for the susceptible group (G5).

Seed yield means for each group of genotypes (Fig. 1c) ranged from 2207 (G3) to 3178 kg ha^{-1} (G1). The mean yield for the three groups associated with partial resistance (G1, G2 and G3) did not differ significantly from the mean for both the intermediate resistant and the susceptible groups (G4 and G5) (Table 4), probably due to the 30% lower yield for the resistant control (G3) in comparison with yield for the putative resistant groups (G1 and G2). However, means of WMI (Fig. 1d), WMSI (Fig. 1e) and weight of sclerotia (Fig. 1f) for both the intermediate resistant and the susceptible groups (G4 and G5) were 34%, 54%, and 54% greater, respectively, than the means for G1, G2 and G3. The means of WMI and WMSI for both G1 and G2 did not differ significantly from those for the resistant control (G3), but weight of sclerotia was 48% greater for the G3. Differences between means of the putative resistant groups (G1 vs. G2) of either yield or weight of sclerotia were non-significant. However, plants of the G1 had 20% less WMI and 27% less WMSI than did plants of the G2. The intermediate resistant genotype had approximately 35% less WMI and WMSI and yielded 14% more than the susceptible genotypes (G4 vs. G5). The highest weight of sclerotia was produced in Viçosa (2017) by plants of the susceptible group (approximately 50 kg ha^{-1}).

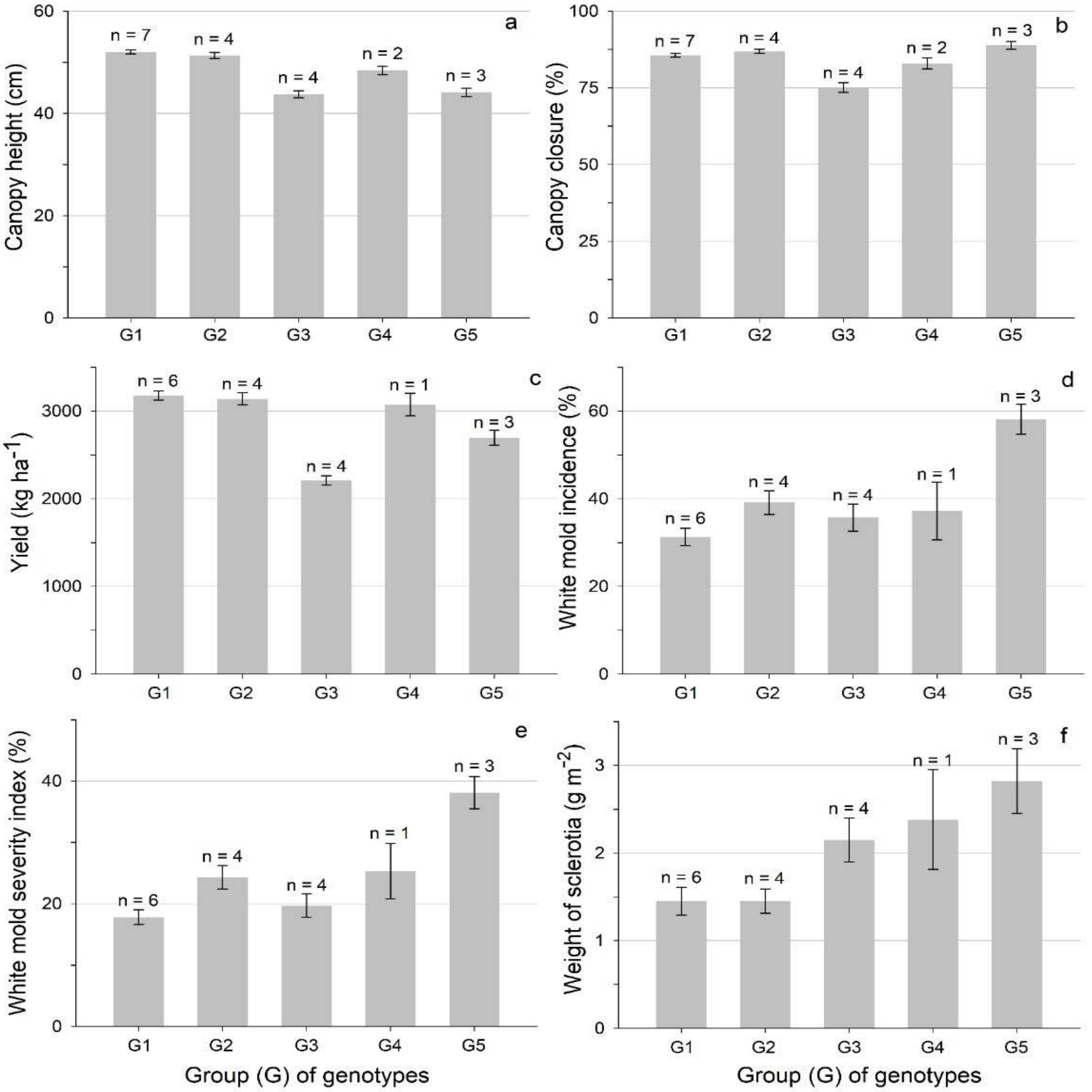

Fig 1 Mean (±SE) canopy height and closure, seed yield and variables related to WM for each group (G) of genotypes: G1 = selected for resistance in 2008-2011 (VC17, CNFC10432, CNFC10720, CNFC10722, CNFC10798, CNFC11990, Vereda), G2 = selected for resistance in 2013-2014 (VC26, VC27, CNFC11946, CNFCMG-11-06), G3 = resistant controls (A195, G122, Cornell605, Ouro Branco), G4 = selected for intermediate resistance (Pérola, Estilo), G5 = selected for susceptibility (Ouro Negro, Ouro Vermelho, Majestoso). Data of the genotypes VC17 and Pérola, which were infected by anthracnose, were not used for mean estimation of seed yield and WM variables. After the letter n above the bars are the number of genotypes used for the mean estimation.

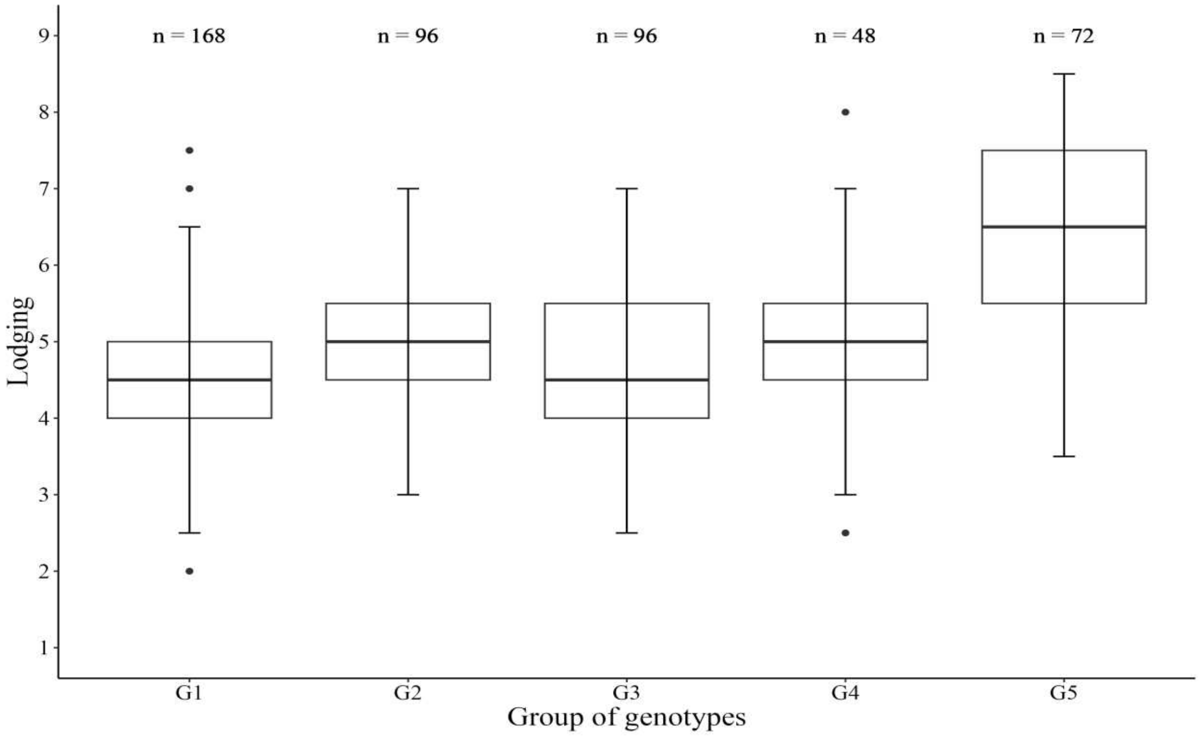

Fig 2 Boxes plots of lodging at harvest for groups (G) of bean genotypes. G1 = selected for partial resistance in 2008-2011 (CNFC10432, CNFC10720, CNFC10722, CNFC10798, CNFC11990, Vereda, and VC17), G2 = selected for partial resistance in 2013-2014 (VC26, VC27, CNFC11946, CNFCMG-11-06), G3 = resistant controls (A195, G122, Cornell605, and Ouro Branco), G4 = selected for intermediate resistance (Estilo, Pérola), G5 = selected for susceptibility (Ouro Negro, Ouro Vermelho and Majestoso). Boxes represent the median (middle bar) and interquartile range (IQR, from the 25th to 75th percentile). Whiskers extend to minimum and maximum values within 1.5 times the IQR. Dots outside the vertical bars were considered outliers. n = number of observations.

Table 4 *P* values for the orthogonal contrasts

Group of genotypes[a]	Canopy height[b] (cm)	Canopy closure[c] (%)	Seed yield[c] (kg ha^{-1})	White mold incidence[d] (%)	White mold severity index[d] (%)	Weight of sclerotia[b] (g/m²)
G1-G3 vs. G4,G5	<0.001	0.002	0.532	<0.001	<0.001	<0.001
G1,G2 vs. G3	<0.001	<0.001	<0.001	0.834	0.354	0.001
G1 vs. G2	0.271	0.313	0.584	<0.001	<0.001	0.967
G4 vs. G5	<0.001	0.001	0.002	<0.001	<0.001	0.291

[a] G1 = selected for resistance in 2008-2011 (VC17, CNFC10432, CNFC10720, CNFC10722, CNFC10798, CNFC11990, Vereda), G2 = selected for resistance in 2013-2014 (VC26, VC27, CNFC11946, CNFCMG-11-06), G3 = resistant controls (A195, G122, Cornell605, Ouro Branco), G4 = selected for intermediate resistance in 2008-2011 (Pérola, Estilo), G5 = selected for susceptibility in 2008-2011 (Ouro Negro, Ouro Vermelho, Majestoso).

[b] Evaluated in four trials.

[c] Evaluated in six trials.

[d] Evaluated in five trials.

Among the genotypes of the resistant control group (G3), G122 had the lower canopy height (40.7 cm) and canopy closure (67.9%), both evaluated at the R7 growth stage (Table S2). Means of WMI and WMSI for the genotypes of the G3 were, respectively: A195 (26% and 14%), Ouro Branco (32% and 16%), G122 (37% and 23%), and Cornell605 (48% and 26%). Production of sclerotia, in g m-2, were: G122 (3.32), Cornell605 (2.12), Ouro Branco (1.66), and A195 (1.52). We observed that plants of the large-seeded genotypes (control group) produced heavier sclerotia [sclerotium mean of 17.1 ± 4.2 (SD) mg] than plants of the small-seed genotypes [12.1 ± 4.0 (SD) mg]. For the calculation of these weights, only the sclerotia mixed with seeds after plant threshing were used. Mean seed yields, in kg ha^{-1}, were: A195 = 2552, Ouro Branco = 2415, G122 = 1988, and Cornell605 = 1875.

Except for Oratórios (2016) and Viçosa (2016), the means of WMI and WMSI for the G3 were lower than those for the other groups of genotypes (Table S3). In 2016, means of WMI and WMSI for the G3 were 2-fold higher compared with those for the G1. Differently from 2015 and 2017, in 2016 approximately 50 mm of rainfall (Table 5) were recorded at the preflowering stage of the G122 (the earliest genotype) or during the flowering stage (Table 1) of the other Andean genotypes (A195, Cornell605, and Ouro Branco). Most of the small-seeded genotypes, however, reached 50% flowering between seven and nine days later than

A195, Cornell605, and Ouro Branco. In 2016, also the mean of weight of sclerotia for G3 was much higher than that for either the G1, G2 or G4 (Table S3).

Table 5 Cumulative precipitation for each month during the experimental period in the three years of trials conducted in two districts of the state of Minas Gerais, Brazil

Month	Rainfall in mm					
	2015		2016		2017	
	Viçosa[a] (L/M)	Oratórios[a] (absent)	Viçosa[a] (M/H)	Oratórios[a] (L/M)	Viçosa[a] (M/H)	Oratórios[a] (M/H)
April	26.8	25.7	28.4	41.2	44.8	9.8
May	63.8	46.0	14.6	0.0	51.4[b]	48.0
June	13.2	6.8	58.8[c]	49.1[d]	18.6[e]	6.0
July	31.6[f]	22.6	0.0	0.0	1.8	0.0
August	7.4	9.2	9.8	5.3	0.8	0.0
September	84.4	91.6	19.8	31.5	14.0	0.0

[a] White mold pressures between parenthesis: L = low, M = moderate, and H = high.

[b] 49 mm was recorded between 20 and 22 May.

[c] 50 mm was recorded between 2 and 4 June.

[d] 47 mm was recorded between 2 and 6 June.

[e] 11 mm was recorded on 12 June and 5 mm on 14 June.

[f] 25 mm was recorded on 26 July.

4. Discussion

We found that the genotypes not selected for partial resistance to WM (i.e. those with intermediate resistance and susceptibility) had higher levels of WM than those that embrace putative resistance (10 genotypes) and well-known resistance (A195, G122, Cornell605, and Ouro Branco). The levels of WM for the 10 small-seeded genotypes selected for partial resistance were like those found for the Andean genotypes with well-known resistance (control). In addition, the genotypes selected for resistance yielded 43% more than the control group. These results confirm conclusions of Lima et al. (2020) that high-yielding genotype with partial resistance may be selected from VCU field trials conducted under WM pressure, followed by the evaluation of the genotypes (included a resistant control) in fields infested with sclerotia of *S. sclerotiorum*. In the current study, we add the information that plants of the genotypes selected for partial resistance generally produce much lower amount of sclerotia than the other genotypes (control, intermediate resistant, and susceptible). These results are consistent with previous studies in which it was found that a WM-susceptible bean cultivar produced between 2.3-fold (Teixeira et al. 2019) and 3.2-fold (Vieira et al. 2022) greater weight of sclerotia than did the partially resistant line VC17 (also used in the present study) during the dry season in Brazil. *S. sclerotiorum* survives as sclerotia in the soil, where they may remain viable for 5 years or more (Schwartz and Singh 2013). Sclerotia germinate infecting bean plants directly (myceliogenically) or, more commonly, forming apothecia (carpogenically) and then ascospores. Airborne ascospores infect dead host tissues, mainly senescent blossoms. Thus, the use of bean genotypes with partial resistance to WM may also reduce the amount of sclerotia left on the soil surface after bean harvest. Hence, the use of small-seeded genotypes with WM-resistant may persistently reduce the primary source of inoculum in the bean fields during the dry season in Brazil.

In the Mid-western and Southeastern regions of Brazil, dry and sunny days predominate during the dry season, mainly during the winter. In this study as well as in the study of Lima et al. (2020), it was observed that sometimes the last rainfall events (associated with cloudy days) of the fall season coincide with either the preflowering or flowering stages of the early maturing genotypes (resistant group). Plants are more susceptible to WM at these two growth stages (Viteri et al. 2015) and continuous soil moisture favors apothecia production (Matheron and Porchas 2005). Thus, the rainfall events registered at either growth stage help to explain the relatively high levels of WM on the well-known resistant group in certain years. However, differently from the Mesoamerican genotypes, the Andean genotypes used here have high levels of physiological resistance to WM (Sing et al. 2007, Pascual et al. 2010, Schwartz and Singh 2013, Lehner et al. 2015, Robison et al. 2018, Lima et al., 2020), usually associated with some avoidance mechanisms (Balasubramanian et al. 2014; Lehner et al. 2015, Lima et al., 2020). In the present study as well as in the study of Miklas et al. (2013), Hoyos-Villegas et al. (2015), and Lima et al. (2020) the Andean genotypes exhibited open canopy and resistance to lodging, traits associated with avoidance mechanisms. For the dry season in Brazil, it appears that the time of flower appearance (phenological trait) has more importance for the resistance to WM than physiological mechanisms, considering that A195, G122 and Cornell605 exhibited high levels of physiological resistance to an isolate of *S. sclerotiorum* collected from mature beans in the same area used to conduct three out of six trials of the present study (Lehner et al. 2015). Thus, late flowering genotypes was confirmed as an important avoidance mechanism for bean during the dry season in Brazil. This trait associated with other traits associated with avoidance mechanisms, especially lodging resistance, canopy porosity and height are important for reducing WM in the field in regions with similar rainfall regime found in the dry season in Brazil. In the semiarid states of the

USA under irrigation, studies also support the importance of plant architecture to limit fungal establishment and development. In humid regions or season, however, the importance of physiological resistance increases (Ender and Kelly, 2005).

The group with well-known resistant (control) yielded 488 kg ha^{-1} less than the group of the susceptible cultivars and 952 kg ha^{-1} less than the group of the 10 genotypes selected for partial resistance to WM. Thus, the early maturing control group exhibited low yield potential, supporting the statement of Miklas et al. (2013) that Andean beans have inherently less yield potential than Mesoamerican beans. In Brazil, Lehner et al. (2015) found that A195, G122 and Cornell605 had low WM ratings in the field as well as in greenhouse (straw test) trials, but G122 exhibited lower yield in the field (1701 kg ha^{-1}) than A195 and Cornell605 (around 3000 kg ha^{-1}). In the current study, G122 confirmed its low yield potential. However, differently from the results obtained by Lehner et al. (2015), G122 and Cornell605 were apparently more susceptible to WM than A195. The large-seeded cultivar Ouro Branco is the line WAF16 from the International Center for Tropical Agriculture. It was released in 1993 for commercial production in the state of Minas Gerais, Brazil. In the study of Lima et al. (2020), Ouro Branco was selected for partial resistant in VCU field trials. After that, Ouro Branco exhibited partial resistance to WM in both greenhouse and field trials. In the field trials of the previous study, Ouro Branco yielded 24% less than A195. In the present study, however, A195 and Ouro Branco had similar WM infection, production of sclerotia and yield, suggesting that Ouro Branco deserve further consideration as a source of partial resistance well adapted to the Brazilian conditions together with A195.

In the five trials where bean plants were infected with *S. sclerotiorum*, the levels of WM for the genotypes selected for partial resistance in the 2013-214 VCU trials were greater compared with those for the genotypes selected for partial resistance in the 2008-2011 VCU trials. In both set of VCU trials, the genotypes were generally selected under high or moderate/high WM pressure. The likely explanation for this difference in WM intensity may be the greater opportunity for selection of the genotypes from the 2008-2011 VCU trials compared to those lines from the 2013-2014 VCU trials. The genotypes from the 2013-2014 were selected based only on two VCU trials. For the genotypes from the 2008-2011 trials, however, 13 genotypes were selected from at least two VCU trials followed by evaluations in six advanced trials (Lima et al., 2020). From the 13 genotypes selected in the VCU trials, we choose for the advanced trials of the present study the seven more productive genotypes with relatively less WM infection in the previous advanced trials. However, regardless of their period of selection (2008-2011 or 2013-2014), genotypes produced similar amount of sclerotia and seed yield. Therefore, genotypes selected for partial resistance in the 2013-214 trials deserve further evaluations under WM pressure in the dry season.

5. Conclusion

Our results associated with those of Lima et al. (2020) reinforce the evidence that small-seeded genotypes originally bred for high yield and foliar diseases resistance may exhibit partial resistance to WM and may achieve grain yield as high as 3500 kg ha^{-1} under high WM pressure in the dry season in Brazil. Evidence also supports that the partial resistance of the small-seeded genotypes is mainly due to avoidance mechanisms such as phenological (late maturing genotypes) and morphological (as tall and porous canopies, and lodging resistance) traits.

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7. Supporting information

Table S1 Seed yield, white mold (WM) rating, and plant lodging at harvest of 25 small-seeded genotypes of carioca market class in two VCU trials

Genotype[a]	**Mean seed yield (kg ha^{-1})**			**Median WM rating**[b] **(1-9)**		**Median lodging rating**[c] **(1-9)**	
	2013	2014	Mean	2013	2014	2013	2014
VC27	**3188**	**3401**	**3295**	**5.0**	**5.0**	**3.5**	**6.0**
VC26	**3088**	**3044**	**3066**	**3.0**	**5.0**	**3.5**	**5.5**
CNFC11946	**2571**	**3477**	**3024**	**5.5**	**5.0**	**3.5**	**5.0**
Majestoso	2779	2881	2830	5.5	4.0	3.5	5.0
VC24	2075	3411	2743	7.0	4.0	4.0	4.5
E09/10-27	2938	2510	2724	6.0	4.5	3.5	5.0
CNFCMG-11-06	**2869**	**2572**	**2721**	**5.0**	**6.0**	**3.5**	**5.0**
Madrepérola	2863	2563	2713	6.5	7.0	4.0	6.5
VC29	3050	2260	2655	5.5	6.0	4.0	6.0
CNFC10429	2063	3212	2638	4.5	3.0	3.8	4.0
E09/10-28	2608	2663	2636	5.7	5.0	3.8	5.0
E09/10-8	2546	2462	2504	6.0	6.5	4.0	6.0
VC30	2663	2343	2503	5.0	5.5	4.0	6.5
E09/10-7	2738	2240	2489	5.5	6.5	3.5	5.5
Ametista	1950	2989	2470	5.0	3.5	3.5	4.0
VC25	2321	2534	2428	6.0	5.5	3.8	5.0
E09/10-5	2738	2092	2415	6.0	6.0	3.8	5.5
CNFCMG-11-13	2342	2297	2320	4.5	5.0	3.5	4.0
CNFCMG-11-08	1983	2439	2211	6.0	5.0	3.8	5.0
E09/10-15	2096	2134	2115	7.0	6.0	3.5	5.5
Pérola	1671	2548	2110	7.0	6.0	4.0	6.0
Talismã	2229	1872	2051	5.5	6.0	4.0	6.0
VC28	2167	1869	2018	6.5	5.0	4.5	6.0
CNFCMG-11-07	1729	1957	1843	7.5	7.0	4.0	5.0
E09/10-10	1663	1183	1423	8.0	8.0	4.0	6.0
LSD (< 0.05)	570	659	-	-	-	-	-

[a] Genotypes selected for partial resistance to WM are in bold. Cultivars used for comparison: Majestoso, Madrepérola, Ametista, Pérola, and Talismã.

[b] 1 = no visible symptoms, 9 = very severe symptoms (Lehner et al. 2015).

[c] 1 = no lodging and 9 = all plants completely lodged (Lima et al. 2020).

Table S2 Mean (± SE) values for variables assessed in four (canopy closure and sclerotia weight), five (white mold incidence and severity index), or six (canopy height and yield) advanced trials established in two districts od the state of Minas Gerais, Brazil

Genotype[a]	Canopy height[b] (cm)	Canopy closure[b] (%)	WMI[c] (%)	WMSI[c] (%)	Sclerotia weight[d] ($g\ m^{-2}$)	Yield ($kg\ ha^{-1}$)
CNFC10432	53.2±0.8	84.9±1.8	29.5±4.7	18.2±3.0	1.45±0.36	3463±138
CNFC10720	52.2±0.6	83.9±1.7	31.4±4.9	17.5±3.2	1.71±0.44	3461±133
CNFP11990	54.4±0.8	87.2±1.8	26.6±3.9	14.7±2.2	1.11±0.37	3322±138
CNFCMG11-06	54.9±1.2	87.8±1.1	42.4±6.1	27.7±4.3	1.64±0.30	3270±155
VC26	48.1±1.1	89.8±1.3	43.6±5.9	26.5±4.1	1.52±0.34	3241±124
CNFP10798	54.3±1.1	87.3±1.2	36.8±5.2	21.7±3.3	1.50±0.38	3206 ± 87
VC27	50.5±1.1	86.3±1.4	38.9±5.4	23.7±3.5	1.35±0.25	3199±158
Estilo	49.2±0.9	84.3±1.1	37.2±6.6	25.3±4.5	2.39±0.57	3074±129
CNFC10722	51.5±0.9	83.1±1.2	28.4±5.1	16.2±2.9	1.59±0.42	2979 ± 71
Ouro Vermelho	40.8±1.2	91.8±1.2	61.1±5.5	38.1±4.0	3.68±0.81	2956±152
CNFC11946	51.6±0.8	83.8±1.7	31.6±4.5	19.3±2.9	1.31±0.26	2852±121
VC17	49.5±1.5	86.4±1.8	37.1±4.3	18.7±2.4	0.84±0.14	2766±187
Majestoso	46.9±1.1	85.8±2.0	46.1±7.0	30.6±5.2	2.40±0.52	2646±120
Vereda	49.0±0.9	86.6±1.2	34.9±6.2	18.7±3.6	1.31±0.43	2638±110
A 195	46.1±1.3	77.6±2.6	25.8±5.0	13.7±2.8	1.52±0.36	2552 ± 77
Ouro Negro	44.6±1.4	88.9±3.0	67.3±4.3	45.6±3.8	2.39±0.50	2485±157
Pérola	47.6±1.2	81.6±3.5	27.5±4.1	14.3±2.9	0.75±0.19	2466±116
Ouro Branco	47.6±1.4	78.9±2.6	32.1±5.1	16.0±2.7	1.66±0.35	2415 ± 92
G 122	40.7±1.2	67.9±4.0	37.1±7.1	23.1±4.6	3.32±1.17	1988 ± 96
Cornell605	41.4±1.3	76.1±2.9	47.6±6.4	26.1±4.2	2.12±0.36	1875±103

[a] Genotypes selected for partial resistance to white mold in VCU trials are in bold.

[b] Evaluated at pod filling.

[c] WMI = white mold incidence, WMSI = white mold severity index.

[d] Sclerotia collected on the soil surface + sclerotia mixed with seeds.

Table S3 Means (± SE) of white mold incidence (WMI) and severity index (WMSI), weight of sclerotia on soil surface + sclerotia mixed with seeds (WESC) in five trials carried out in Viçosa (V) and Oratórios (O)

Variables	Municipality (year)	Group of genotypes[a] G1	G2	G3	G4	G5
WMI (%)	V (2015)	14.5±2.3	15.2±2.3	9.0±2.7	17.3±12.1	39.5±7.8
	O (2016)	6.9±1.5	12.1±1.6	17.1±4.5	1.0±0.7	32.7±6.2
	V (2016)	32.2±2.6	48.6±3.1	66.9±5.7	57.3±5.9	67.8±4.0
	O (2017)	54.7±3.3	67.0±3.2	43.3±5.5	65.3±9.8	84.6±1.9
	V (2017)	48.2±2.8	52.7±3.7	41.9±3.9	45.0±11.0	66.1±5.4
WMSI (%)	V (2015)	7.5±1.4	8.5±1.4	4.7±1.5	10.4±7.7	23.9±5.3
	O (2016)	3.4±0.8	6.1±1.0	7.8±2.2	0.8±0.5	17.2±3.7
	V (2016)	19.1±1.7	29.9±2.1	38.3±4.0	34.2±2.3	46.1±3.3
	O (2017)	31.0±1.8	40.5±2.5	24.0±3.4	44.3±8.1	57.4±1.8
	V (2017)	28.3±2.3	36.6±3.3	23.9±2.9	37.0±7.4	45.9±4.7
WESC ($g\ m^{-2}$)	V (2015)	-[b]	-	-	-	-
	O (2016)	0.05±0.02	0.07±0.02	0.20±0.07	0.02±0.02	0.23±0.06
	V (2016)	0.69±0.10	1.15±0.13	3.71±0.61	1.92±0.31	1.59±0.21
	O (2017)	3.25±0.33	2.26±0.18	2.61±0.38	4.86±1.27	4.43±0.39
	V (2017)	1.79±0.24	2.34±0.27	2.09±0.30	2.74±0.90	5.04±0.82

[a] G1 = CNFC10720, CNFC10432, CNFP11990, CNFP10798, CNFC11946, CNFC10722, Vereda; G2 = VC26, VC27, CNFC11946, CNFCMG-11-06; G3 = A195, Cornell605, Ouro Branco, G122; G4 = Estilo; G5 = Ouro Vermelho, Ouro Negro, Majestoso.

[b] Not evaluated.

CHAPTER 2

BETWEEN- AND IN-ROW PLANT DENSITY FOR TYPE II COMMON BEANS WITH PARTIAL FIELD RESISTANCE TO WHITE MOLD

VIÇOSA - MINAS GERAIS
2022

ABSTRACT

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, September, 2022. **Between- and in-row plant density for type II common beans with partial field resistance to white mold.** Adviser: José Eustáquio de Souza Carneiro. Co-adviser: Rogério Faria Vieira.

High yield can be obtained with type II beans using high plant population. However, high plant population favors diseases, especially white mold. Our objective was to evaluate the effects of between-row spacing (0.25 or 0.50 m) combined with in-row plant density (7, 10, 13 or 16 plants m^{-1}) levels on yield and diseases on type II bean genotype partially resistant to white mold. The carioca line CNFC 10720 was used. The experimental design was a randomized complete block with four replications. White mold pressures were low in the 2019 and 2020 trials and absent in the 2018 trial. Mean grain yield in each of the three trials ranged from 1591 (in 2018, with drought stress) to 3121 kg ha^{-1}. In the two trials without drought stress, canopy closure was greater at 0.25 m and at 13-16 plants m^{-1}. At high plant population, plants were taller, had reduced stem diameter, but insertion of the first pod was not affected by treatments. On average for 2019 and 2020 trials, yield at 0.25 m was 28% higher than yield at 0.50 m ($p < 0.001$). Yield was maximized with 10 to 16 plants m^{-1}. In conclusion, plant population for type II genotypes with partial resistant to white mold higher that that currently recommended may improve seed yield. However, more studies are necessary under condition of diseases pressure, especially white mold, before a conclusion can be reached.

Keywords: *Sclerotinia sclerotiorum*. Dry bean. Plant population. Growth habit.

RESUMO

TEIXEIRA, Pablo Henrique, D.Sc., Universidade Federal de Viçosa, setembro de 2022. **Espaçamento e densidade de feijoeiros do tipo II com resistência parcial de campo ao mofo-branco.** Orientador: José Eustáquio de Souza Carneiro. Coorientador: Rogério Faria Vieira.

Maior produtividade pode ser obtida sob alta população de plantas em feijoeiros do tipo II. No entanto, alta população de plantas favorece doenças, especialmente o mofo-branco. Nosso objetivo foi avaliar os efeitos de espaçamento entre fileiras (0,25 m ou 0,50 m) combinado com densidade de plantas (7, 10, 13 ou 16 plantas m^{-1}) na produtividade e doenças em feijoeiro do tipo II parcialmente resistente ao mofo-branco. Foi utilizada a linhagem carioca CNFC 10720. O delineamento foi em blocos ao acaso com quatro repetições. As pressões de mofo-branco foram baixas nos ensaios de 2019 e 2020 e ausente em 2018. A produtividade média nos ensaios variou de 1591 (em 2018, sob déficit hídrico) a 3121 kg ha^{-1}. Nos dois ensaios sem déficit hídrico, a cobertura do dossel foi maior sob 0,25 m e 13-16 plantas m^{-1}. Sob alta população de plantas, as plantas ficaram mais altas, tiveram o diâmetro de caule reduzido, mas a altura de inserção da primeira vagem não foi afetada pelos tratamentos. Na média dos ensaios de 2019 e 2020, a produtividade sob 0,25 m foi 28% maior que a produtividade sob 0,50 m ($p < 0.001$). A produtividade foi maximizada com 10 a 16 plantas m^{-1}. Concluímos que a população de plantas maior para genótipos do tipo II com resistência parcial ao mofo-branco melhora a produtividade comparada a atual recomendação. No entanto, mais estudos são necessários sob condições de pressão de doenças, especialmente mofo-branco, antes que uma conclusão possa ser alcançada.

Palavras-chave: *Sclerotinia sclerotiorum*. Feijão de inverno. População de plantas. Hábito de crescimento.

1. Introduction

Brazil produced 2,231,200 tons of common bean (*Phaseolus vulgaris* L.) in the 2020-2021, with an average grain yield of 1,418 kg ha^{-1}. In Brazil, the production originated from three growing seasons: spring-summer (38% of total), summer-fall (30%) and fall-winter (32%). Minas Gerais State, located in the southeastern region, is the main producers of common bean in the fall-winter season with a production of 175,900 tons and an average yield of 2,546 kg ha^{-1} in 2021 (Conab, 2021). In this season, the temperature is moderate and rains are scarce, thus irrigation is needed. These conditions are favorable for fungal diseases as anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magn.) Scribner], angular leaf spot [*Pseudocercospora griseola* (Sacc.)], and white mold (WM) [*Sclerotinia sclerotiorum* (Lib.) de Bary], that are important constraint in obtaining high yield during the fall-winter season (Ramalho et al., 2014).

Currently, in Brazil most of the common bean cultivars are type II or type III growth habit. Type II cultivars are characterized for tall plants, narrow and porous canopy, reduced branching and spread pods through stem, and generally reduced lodging at maturity harvest. Plants of type III growth habit are prostrate or semiprostrate, have long branching and pods are concentrated at the base of canopy, and generally the plants have some levels of lodging at maturity harvest. There is a trend of producers to use type II cultivars, because greater air circulation into the canopy decreases foliar diseases and WM, and facilitates mechanical harvesting of plants (Ramalho et al., 2016).

The currently recommendation for type II growth habit of common bean is 0.40-0.50 m between-row spacing (BRS) with 11-13 plants m^{-1} (Ramalho et al., 2014) in areas free of *S. sclerotiorum*. Studies conducted in Brazil and Canada suggest that narrower BRS and/or high plant density (PD) may increase the yield of the type II growth habit cultivars (Park et al., 1993; Saindon et al., 1993, 1995; Shimada et al., 2000; Silva et al., 2008; Ziviani et al., 2009). However, high plant population may increase diseases, especially WM. The risk of seed yield reduction due to WM may be decreased when a partially resistant type II genotype to WM is used. Just recently some partially resistance genotypes of Type II growth habit were identified for the fall-winter season (Lima et al., 2020).

The objective of this study was to evaluate the performance of type II bean partially resistant to WM in the field under high plant population conditions in areas infested with sclerotia of *S. sclerotiorum*. We hypothesized that type II beans partially resistant to WM in the field can achieve high yield under high plant population in areas infested with sclerotia.

2. Material and methods

2.1 Experimental locations, climate, and soil characteristics

Three common bean trials were conducted in fields naturally infested with sclerotia of *S. sclerotiorum*: two during the fall-winter season (2018 and 2019) and one during winter-spring season of 2020 in two districts of Zona da Mata region, State of Minas Gerais, Brazil. In 2018, the trial was conducted in Oratórios (20°25'5"S, 42°47'28"W, 492 m a.s.l.). In 2019 and 2020, the trials were conducted in Viçosa (20°45'14"S, 42°52'55"W, 648 m a.s.l.). According to Köppen's classification, the climate in these districts is Cwa: subtropical warm with dry winter (Alvares et al., 2014).

Soil texture composition, in %, was: 31, 44 and 25 (Oratórios) and 53, 24 and 23 (Viçosa) for clay, silt and sand, respectively. The soil pH_{H2O} (1:2.5) was 5.3 in Oratórios and Viçosa. For both districts, the soils had been cultivated for over 20 years with corn (*Zea mays* L.) or fallow system during the spring-summer season and usually with common bean during the fall-winter season.

2.2 Treatment, experimental design, plot, and crop management

Treatments were a combination of BRS (0.25 or 0.50 m) and PD (7, 10, 13 or 16 plants m^{-1}) using elite line CNFC 10720. Seeds were manually sown on either 26 April, 10 May or 4 August with 30% more seeds than planned plant densities and subsequent thinning at V3 developmental stage (first trifoliate leaf) to nearly uniform distances between plants. Line CNFC 10720 belongs to the carioca market class, and it has indeterminate type II growth habit. This line has low physiological resistance to WM (Lima et al., 2013), but exhibited partial resistance to WM in the field due to mostly to avoidance mechanisms (Lima et al., 2015; 2020).

The experimental design was a randomized complete block with four replicates. Each plot had six (0.25 m BRS) or four (0.50) 5-m long rows. The central 4 m^2 were used for data collection.

One month before sowing, Roundup (48% glyphosate; Monsanto do Brasil Ltda.) at 3 L ha^{-1} was applied over the weeds. Between five and eight days before sowing, the soil was disc-plowed to a depth of approximately 0.20 m followed by heavy-disc harrowing twice. Except in 2020, inorganic sources of nitrogen, phosphorus, potassium and molybdenum were used targeting yields above 2500 kg ha^{-1} (Ramalho et al., 2014). Following sowing, the pre-emergency herbicide Dual Gold (96% S-metolachlor; Syngenta Proteção de Cultivos Ltda) at 1.25 L ha^{-1} was applied. Irrigation was provided with sprinklers fixed 1.5 m above ground level at two-day intervals from sowing to seedling emergence. From seedling emergence to harvest, common bean was irrigated once a week with approximately 40 mm of water. In Oratórios the last irrigation was performed at R7 growth stage (pod-formation) due to problems in the irrigation pump. Weeds were controlled using the post-emergence herbicides Flex (250 g L^{-1} fomesafem; Syngenta Proteção de Cultivos Ltda) at 1 L ha^{-1} and Fusilade 250 EW (250 g L^{-1} fluazifop-p-butyl; Syngenta Proteção de Cultivos Ltda) at 0.75 L ha^{-1}. Sucking insects, especially green leafhopper [*Empoasca kraemeri* (Ross & Moore)] were controlled with two or three sprays of the insecticide Evidence 700 WG (70% imidacloprid; Bayer S.A.) at 125 g ha^{-1} during the vegetative stage of plants. The fungicide Nativo (10% trifloxistrobin; 20% tebuconazol; Syngenta Proteção de Cultivos Ltda) at 0.75 L ha^{-1} was sprayed twice at V4 growth stage to manage foliar diseases like angular leaf spot [*Pseudocercospora griseola* (Sacc.)] and anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magn.) Scribner] was usually made by farmers.

2.3 Assessment data

Canopy closure and canopy height were evaluated from V4 (third trifoliate leaf, 34 DAE) to R8 growth stages (83 DAE) at 7-day interval. In Oratórios the last assessment was at 55 days after emergence (DAE). For canopy closure evaluation, plants were observed from one end of the plot (looking down the rows) and visually estimating the proportion of soil surface visible between the rows (100% representing complete ground cover) (Kane & Grabau, 1992). Plant height was determined from the soil surface to the apex of six randomized plants. Stem diameter at 1 cm of the soil surface and height of insertion of the first pod were evaluated in 10 randomized plants one day before the harvest. At harvest, final plant population was determined by counting the number of plants in 4 m^2.

Plants from each plot were threshed. Yields were estimated using seeds at 13% moisture. These grains were used to estimate the 100-seed weight.

2.4 Data analysis

The data were analysed using the software program “Sistema para Análises Estatísticas” (SAEG; Ribeiro Júnior, 2001). Data were analyzed for homogeneity of variance with Bartlett’s test and for normality with Lilliefors’s test. A two-way ANOVA was used to analyses the effects of BRS (0.25 or 0.50 m) and PD (7, 10, 13 or 16 plants m^{-1}) and interaction on stem diameter, height of insertion of the first pod, grain yield and 100-seed weight. The fixed factors were BRS, PD and interaction. The random factor was block. A cross-site analysis was carried out for the two trials in which irrigation was regularly applied during the plant’s life cycle (2019 and 2020). In this analysis, trial (site-year) was treated as a fixed factor. Means of variables affected by BRS were compared by F-test. Tukey’s test ($p < 0.05$) was used to compare means of the variables affected by the levels of PD. For canopy closure and canopy height a descriptive approach was used.

3. Results

3.1 Plant population, general diseases and mean yield

The final plant populations were close to the planned plant population. Except for the lowest PD, plant populations were lower in 2019 and 2020 than in 2018 (Table 1). In 2019 and 2020, WM pressure was very low. This disease was not observed in Oratórios. Angular leaf spot and anthracnose were at low levels in the three trials. Mean grain yield in each of the three trials ranged from 1591 to 3121 kg ha^{-1}.

Table 1 Plant population in the three trials conducted in two districts of Zona da Mata region, State of Minas Gerais, Brazil.

BRS (m)	PD (plants m^{-1})	Planned plant population per hectare (x1000)	Final plant population per hectare (x1000)		
			Oratórios (2018)	Viçosa (2019)	Viçosa (2020)
0.25	7	280	252	257	244
	10	400	399	331	335
	13	520	527	450	464
	16	640	620	566	552
0.50	7	140	139	141	112
	10	200	198	189	183
	13	260	267	241	243
	16	320	326	299	296

Table 2 Levels of significance for the fixed effects of between-row spacing (BRS), plant density (PD) and interactions among these factors on stem diameter, height of insertion of the first pod, grain yield and 100-seed weight in three trials conducted in two districts of the State of Minas Gerais, Brazil.

Trial	Fixed effects	d. f.	Stem diameter	Insertion of the first pod	Grain yield	100-seed weight
Oratórios (2018)	BRS	1	0.011	-	0.075	0.367
	PD	3	0.028	-	0.238	0.430
	BRS x PD	3	0.189	-	0.013	0.214
Viçosa (2019)	BRS	1	0.019	0.213	<0.001	0.534
	PD	3	0.009	0.734	0.102	0.053
	BRS x PD	3	0.706	0.700	0.915	0.985
Viçosa (2020)	BRS	1	0.002	0.410	<0.001	0.702
	PD	3	<0.001	0.439	0.019	0.247
	BRS x PD	3	0.641	0.825	0.390	0.706
Cross-site analysis in Viçosa	T	1	<0.001	<0.001	<0.001	<0.001
	BRS	1	<0.001	0.167	<0.001	0.546
	PD	3	<0.001	0.297	0.012	0.113
	T x BRS	1	0.536	0.999	0.474	0.920
	T x PD	3	0.063	0.818	0.223	0.270
	BRS x PD	3	0.631	0.618	0.739	0.775
	T x BRS x PD	3	0.718	0.959	0.753	0.732

3.2 Canopy closure

Averaged across trials and PD, canopy closure was 1.7-fold greater at 0.25 m than at 0.50 m (Fig. 1) at V4 growth stage (34 DAE). This difference was reduced to 1.1-fold at R8 growth stage (83 DAE). Between 48 (R6) and 69 DAE (R7) was observed the maximum canopy closure (Fig. 1;2).

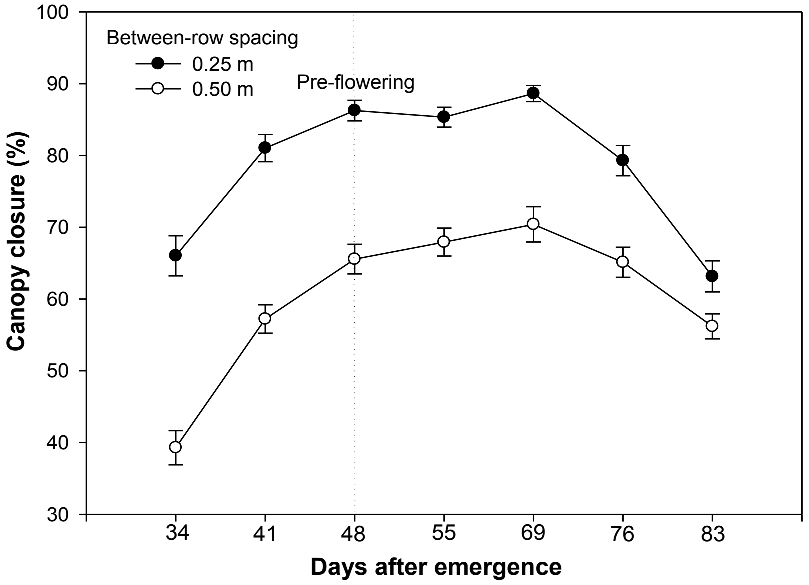

Figure 1 Effect of between-row spacing on canopy closure between 34 and 83 days after emergence averaged over three (between 34 and 55 DAE, n = 48) or two (between 69 and 83 DAE, n = 32) trials. Bars represent standard error.

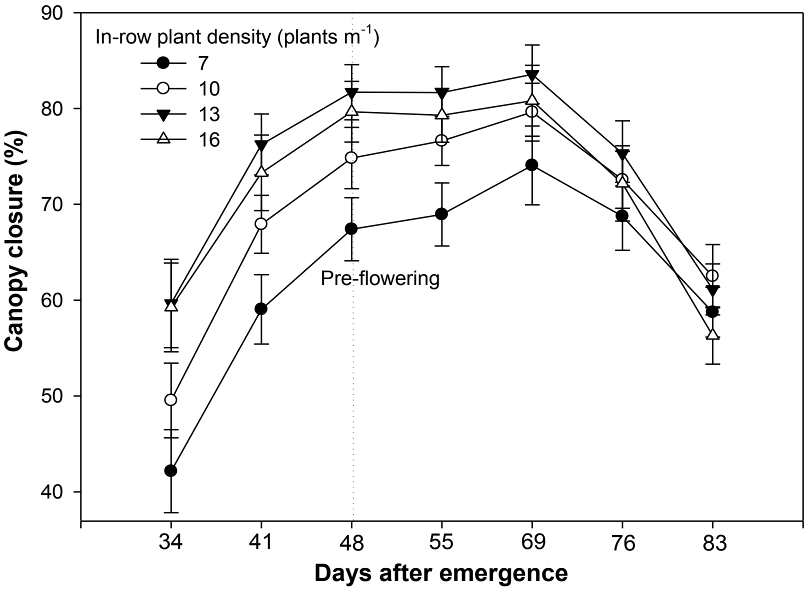

Figure 2 Effect of plant density on canopy closure between 34 and 83 days after emergence over three (between 34 and 55 DAE, n = 48) or two (between 69 and 83 DAE, n = 32) trials. Bars represent standard error.

3.3 Plant height, stem diameter and insertion of the first pod

Plants were approximately 2 cm higher at 0.25 m than at 0.50 m between 34 and 55 DAE. This difference decreased from 69 to 83 DAE (Fig. 3). Maximum plant height was observed at 55 DAE (Fig. 3;4). Between 34 and 55 DAE, plants were taller at 13 and 16 than at 7 and 10 plants m^{-1}. After that, differences in plant height in response to PD were smaller, especially at 83 DAE (Fig. 4).

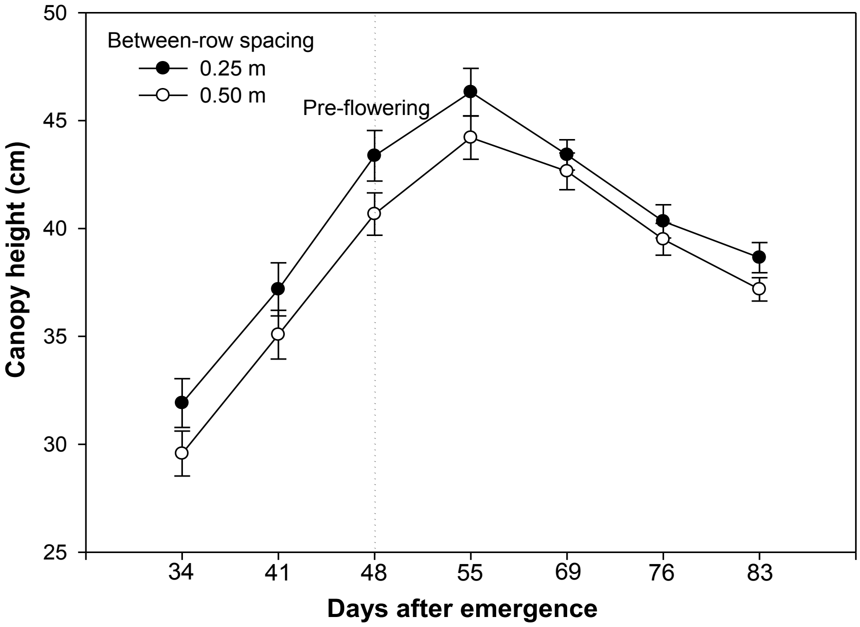

Figure 3 Effect of between-row spacing on canopy height between 34 and 83 days after emergence over three (between 34 and 55 DAE, n = 48) or two (between 69 and 83 DAE, n = 32) trials. Bars represent standard error.

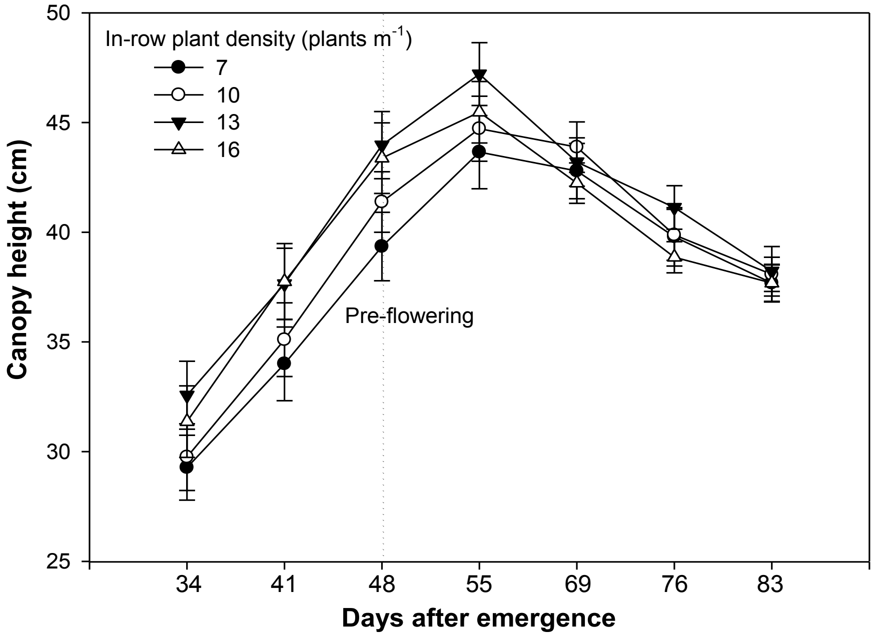

Figure 4 Effect of plant density on canopy height between 34 and 83 days after emergence over three (between 34 and 55 DAE, n = 48) or two (between 69 and 83 DAE, n = 32) trials. Bars represent standard error.

In each trial and in the cross-site analysis, interactions were not significant for stem diameter, but the effect of each single factor was significant for this variable (Table 2). Averaged across trial and PD, stem diameter at 0.50 m were 10% thicker than stem at 0.25 m (Fig. 5). Averaged across trial and BRS, stem diameter at either 7 or 10 plants m^{-1} were 20% and 9% thicker than stem diameter at 16 plants m^{-1}, respectively. In the cross-site analysis, averaged across Viçosa trials and PD, stem diameter at 0.50 m BRS were 9% thicker than stem at 0.25 m (Fig. 6). Averaged across Viçosa trials and BRS, stem diameter at either 7 or 10 plants m^{-1} were 19% and 9% thicker than stem diameter at 16 plants m^{-1}, respectively. BRS, PD, and interactions did not affect height of insertion of the first pod in the trials in Viçosa and also in the cross-site analysis.

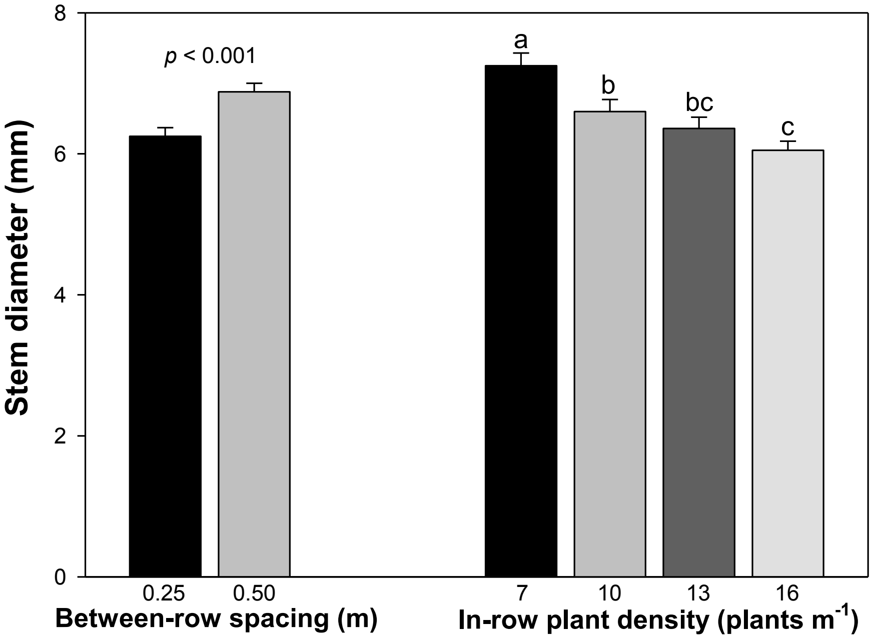

Figure 5 Effect of between-row spacing (n = 48) and plant density (n = 24) on stem diameter in the three trials. In plant density, means with same letter do not differ significantly by Tukey's test at 5% level. Error bars represent standard error of the mean.

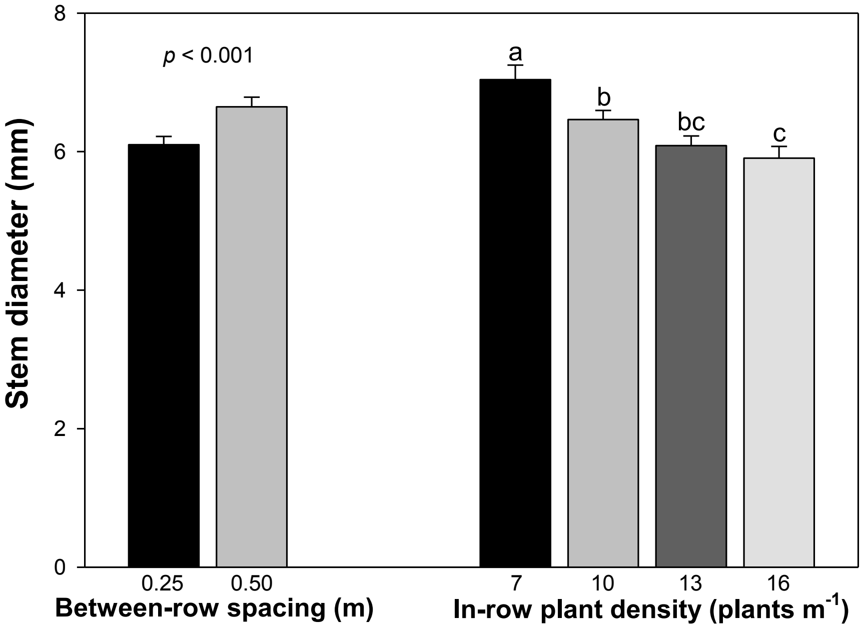

Figure 6 Effect of between-row spacing (n = 32) and plant density (n = 16) on stem diameter in the cross-site analysis. In plant density, means with same letter do not differ significantly by Tukey's test at 5% level. Error bars represent standard error of the mean.

3.4 Grain yield and 100-seed weight

Only in Oratórios (2018), where irrigation was discontinued, the BRS x PD interaction was significant for grain yield (Table 2). At 0.50 m, yield at 13 plants m^{-1} was 30% higher than yields at the other PD (Fig. 7). At 0.25 m, PD did not affect the yield.

BRS x PD interaction on yield was not significant in Viçosa (2019 and 2020) (Table 2). In these trials, however, the single effect of BRS on yield was significant. Averaged across PD, yield at 0.25 m was 31% higher in 2019 and 25% higher in 2020 compared with 0.50 m (Fig. 8). The single effect of PD was significant in Viçosa 2020 (Table 2). Averaged across BRS, yield at 16 plants m^{-1} was approximately 12% higher than the average yield at 7 and 10 plants m^{-1}, but did not differ significantly from 13 plants m^{-1} (Fig. 9).

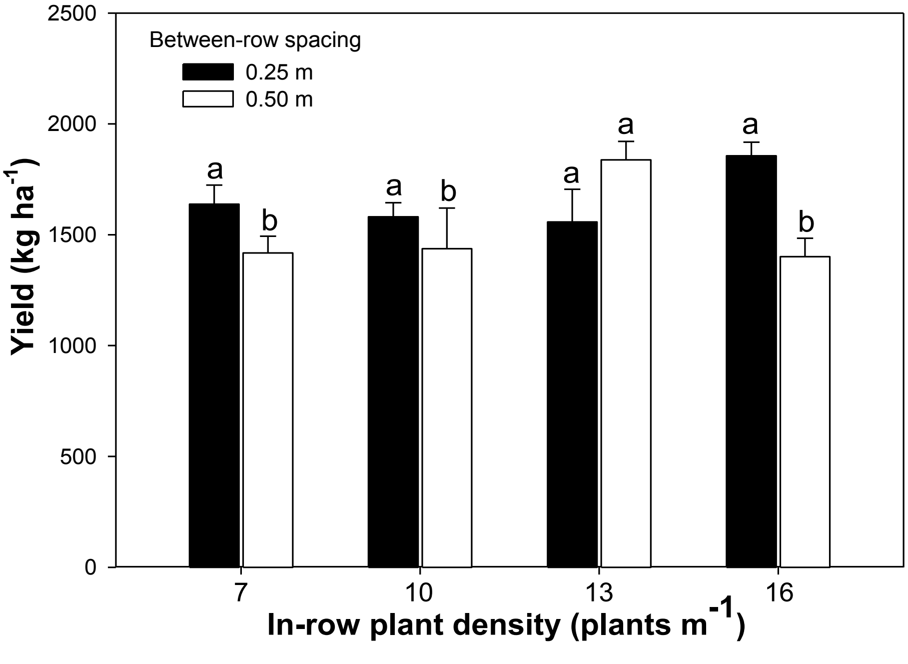

Figure 7 Between-row spacing (n = 16) x plant density interaction on grain yield (n = 4) in Oratórios (2018). In each between-row spacing level, means with same letter do not differ significantly by Tukey’s test at 5% level. Error bars represent standard error of the mean.

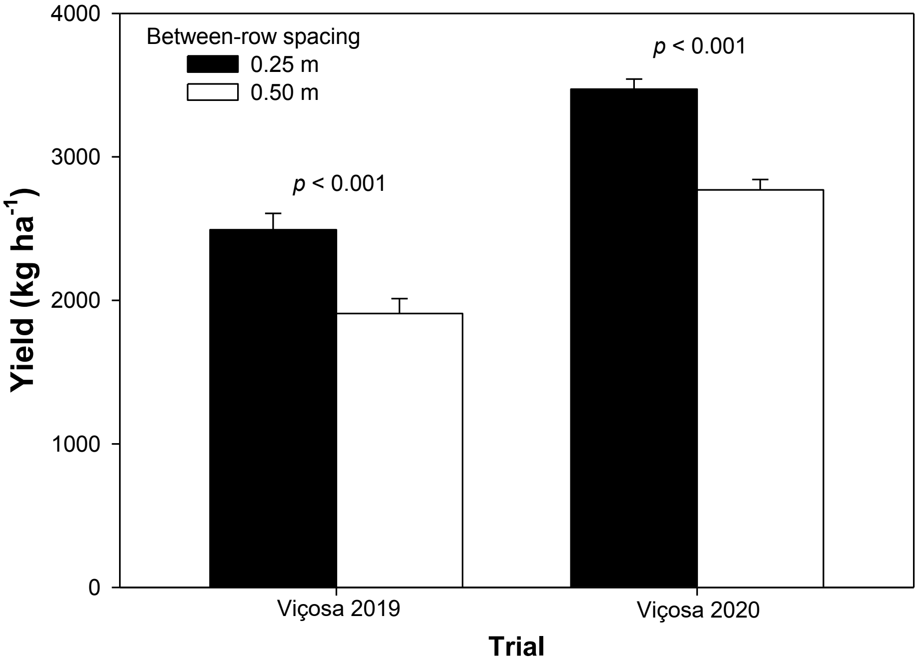

Figure 8 Effect of between-row spacing on grain yield (n = 16), in Viçosa (2019 and 2020). Error bars represent standard error of the mean.

In the cross-site analysis, BRS x PD interaction on yield was not significant (Table 2). However, the effect of each factor on yield were significant. Averaged across Viçosa trials and PD, yield at 0.25 m was 28% higher than yield at 0.50 m. Averaged across Viçosa trials and BRS, yield at 13 plants m^{-1} was 16% higher than yield at 7 plants m^{-1}. This density did not differ significantly from 16 or 10 plants m^{-1} (Fig. 10). Interactions and single effects were not significant in the three trials and in the cross-site analysis for 100-seed weight (Table 2).

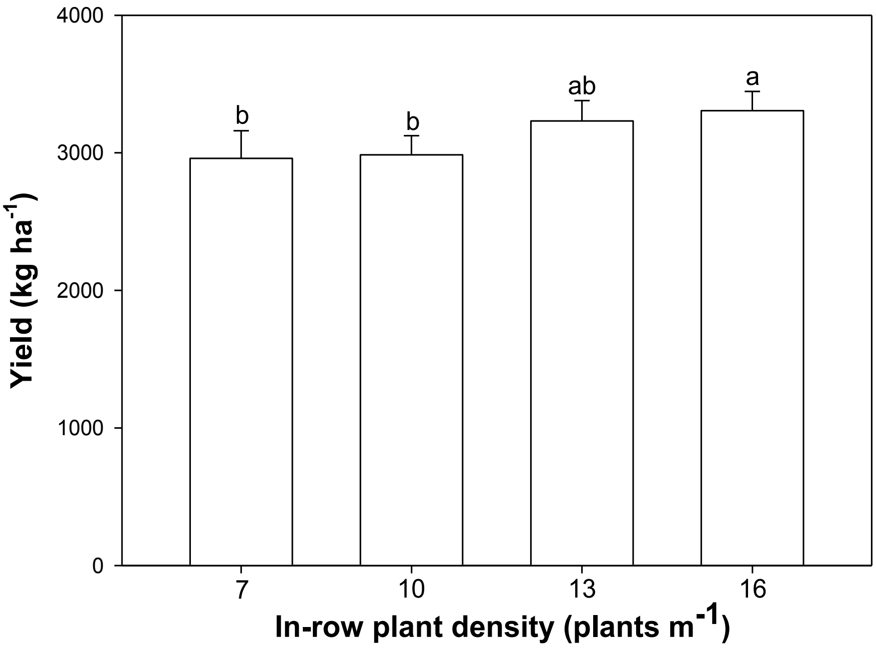

Figure 9 Effect of plant density on grain yield (n = 8), in Viçosa (2020). Means with same letter do not differ significantly by Tukey's test at 5% level. Error bars represent standard error of the mean.

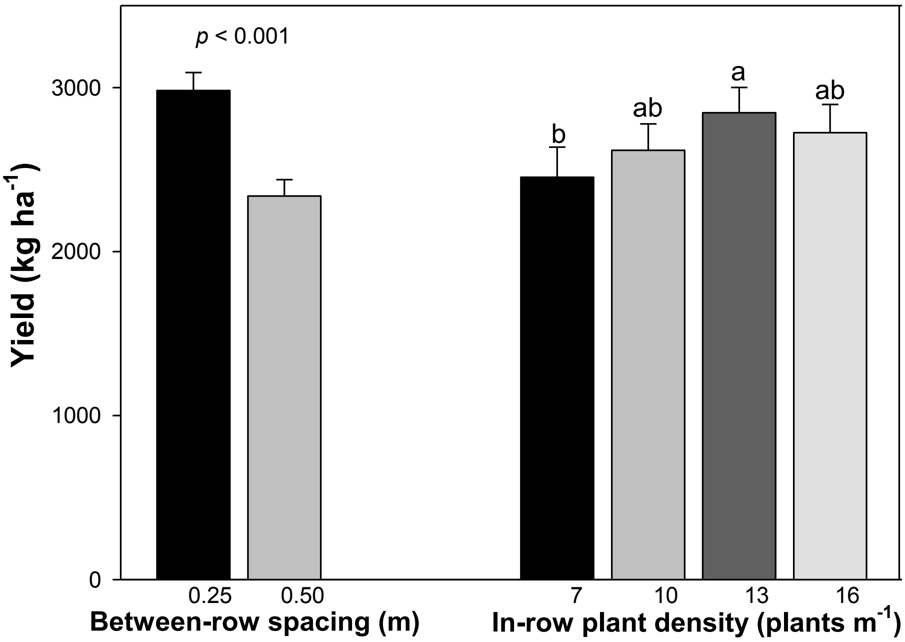

Figure 10 Effect of between-row spacing (n = 32) and plant density (n = 16) on grain yield in the cross-site analysis. In plant density, means with same letter do not differ significantly by Tukey's test at 5% level. Error bars represent standard error of the mean.

4. Discussion

Studies showed that bean of type II growth habit may maximize yield when planted under high plant population (Park et al., 1993; Saindon et al., 1993;1995; Shimada et al., 2000; Silva et al., 2008; Ziviani et al., 2009). However, high plant population may favor diseases, especially WM, due to the high humidity within canopy and on the soil (Blad et al., 1978). With a possible release of beans with type II growth habit with partial resistance to WM (Lima et al., 2020) in the short future, the use of high plant population for this type may reduce the risk of white mold outbreak. It was hypothesized that beans with type II growth habit and partial field resistance to WM maximize yield under high plant population condition in the fall-winter season. To test this hypothesis, three trials were conducted in areas naturally infested with sclerotia of *S. sclerotiorum*. Unfortunately, the pressure of WM and foliar diseases were either absent or low in the trials, indicating the need for more studies under disease pressures, especially under WM pressure. In addition, in one trial irrigation was discontinued from the R7 growth stage to harvest due to problems with the irrigation system. For this reason, this trial was not included in the cross-site analysis. In this case, differently from the other trials, BRS x PD interaction was significant for yield, suggesting a dependence between these factors when a drought stress occur at the end of the reproductive stage. In this trial, PD was only significant when 0.50 m between rows was used: 13 plants m^{-1} seem to be the best density.

In the cross-site analysis with two trials only the single factors were significant, indicating independence of these factors when irrigation is performed adequately. In the cross-site analysis, yield was higher with 0.25 m than with 0.50 m, and 10-16 plants m^{-1} maximized yield (Fig. 10). These results support previous studies (Shimada et al., 2000; Saindon et al., 1995; Silva et al., 2008; Ziviani et al., 2009), which results indicate that type II bean plants may exhibit higher yield when plant population used is greater than that recommended. Under conditions of WM pressure, Lima et al. (2019) found that 11-13 plants m-^{1} was the PD for type II bean that maximized yield without increase WM for a partially resistant genotype when 0.50 m between rows was used.

Canopy closure was maximized with 0.25 m between rows and 13-16 plants m^{-1}. Under this high plant population, a better suppression of weeds may be obtained with a possible reduction of herbicide application (Dusabumuremyi et al., 2014; Liebman et al., 2004). In addition, high plant population lower the risk of crop failure associated with a low percentage of seed germination or seedling death. However, the costs with seeds increase.

The 100-seed weight was not affected by BRS and PD in the present study, as found in other studies (Buzetti et al., 1992; Arf et al., 1995; Dusabumuremyi et al., 2014; Kouam et al., 2020). However, there are studies in which narrower BRS (Shimada et al. 2000; Silva et al., 2008) and higher PD (Ribeiro et al., 2004; Silva et al.,2008; Lima et al., 2019) decreased 100-seed weight. Genotypes and environmental conditions may affect this variable (Ribeiro et al., 2004).

In our study, high plant population increased slightly canopy height up to R6 growth stage. The difference on canopy height among the plant population tested decreased after this stage, probably with either small or no effect on mechanical harvest. In the current study, increasing plant population caused a reduction on stem diameter as was also observed by Ribeiro et al. (2004) and Kouam et al., (2020). According to Vale et al. (2012), stem diameter does not affect the effectiveness of the mechanized harvesting, but may facilitate hand harvesting. Mechanized harvesting may be affected by the first pod insertion (Bertoldo et al., 2010; Hiolanda et al., 2018). In the present study and in the study of Shimada et al. (2000), high plant population did not affect the first pod insertion. However, some studies involving plant population showed that the first pod insertion increased as plant population increased (Alcântara et al., 1991; Lemos et al., 1993), which may improve mechanized harvesting effectiveness. Thus, in general, our study did not suggest any beneficial effect of high plant population on the efficacy of the mechanized harvest, but further studies under WM pressure are needed to better understand this issue.

5. Conclusion

In conclusion, type II cultivars with WM-partial resistance may support high plant population without increasing diseases, but increasing substantially seed yield. However, studies under diseases pressure, especially under white mold pressure, are necessary for a final conclusion can be drawn.

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