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ARTICLE

Effects of seed infection and hydration on the buildup of common bacterial blight and its impact on the yield of dry beans

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Abstract: Common bacterial blight (CBB), caused by *Xanthomonas axonopodis* pv. *phaseoli* (*Xap*), is a serious foliar disease in most of the dry bean (*Phaseolus vulgaris* L.) growing regions. A 4 yr study examined the effects of different sources of infection and seed hydration on CBB development, yield components, and yield in seven resistant or susceptible dry bean lines and cultivars. The five agronomic treatments examined included clean seed, diseased seed, hydrated diseased seed, clean seed with a *Xap* spray, and diseased seed with a *Xap* spray. Disease development, the yield components, and yield were strongly influenced by weather conditions. In comparison with the diseased-seed treatment, the use of clean (disease-free) seed reduced the incidence of CBB leaf infection in the susceptible dry bean cultivars, but no similar benefit was observed in the resistant lines and cultivars. During the three dry growing seasons, the seed-hydration treatment increased the incidence of CBB leaf infection compared with the diseased-seed treatment for the susceptible cultivars but not for the resistant lines and cultivars. In the wet growing season, no significant difference in the incidence of leaf infection was observed between the hydrated-seed and diseased-seed treatments in any of the cultivars, possibly because the wet soil conditions promoted pathogen development within the bean plants that year. Seed hydration did not improve seed yield in the dry years, but sometimes decreased it under wet conditions. Therefore, seed hydration cannot be recommended for use in the production of dry beans.

Key words: Phaseolus vulgaris, common bacterial blight, *Xanthomonas axonopodis* pv. *phaseoli*, seed hydration, yield components.

Résumé : La brûlure bactérienne (CBB — « common bacterial blight ») causée par *Xanthomonas axonopodis* pv. *phaseoli* (*Xap*) est une grave maladie foliaire du haricot (*Phaseolus vulgaris* L.) dans les régions où on le cultive. Lors d'une étude de quatre ans, les auteurs ont examiné l'effet de diverses sources d'infection et de l'hydratation des semences sur le développement de la maladie, les paramètres du rendement et le rendement pour sept lignées et cultivars de haricot résistants ou sensibles à la maladie. Les cinq traitements examinés étaient les suivants : graines non infectées, graines infectées, graines infectées hydratées, graines non infectées pulvérisées avec du *Xap* et graines infectées pulvérisées avec du *Xap*. L'évolution de la maladie, les paramètres du rendement et le rendement ont été fortement influencés par les conditions météorologiques. Comparativement à l'usage de semences infectées, l'usage de graines non infectées diminue la proportion de feuilles atteintes par la BB chez les cultivars

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sensibles, mais aucun avantage analogue n'a été observé chez les lignées et les variétés résistantes. Au cours des trois périodes végétatives arides, l'hydratation des semences a accru l'incidence de l'infection des feuilles par la BB chez les plants sensibles issus de graines infectées, mais pas chez les plants des lignées et des cultivars résistants. Lors des périodes végétatives humides, les auteurs n'ont pas relevé d'écart important entre l'incidence de la maladie foliaire chez les plants des différents cultivars issus de graines hydratées et de graines infectées, peut-être parce que le sol détrempé avait favorisé la prolifération de l'agent pathogène dans les plants de haricot cette année-là. L'hydratation des semences n'a pas amélioré le rendement les années sèches, mais l'a diminué à l'occasion, les années humides. On en conclut que l'hydratation des graines ne peut être recommandée pour la culture du haricot. [Traduit par la Rédaction]

Mots-clés : *Phaseolus vulgaris*, brûlure bactérienne, *Xanthomonas axonopodis* pv. *phaseoli*, hydratation des semences, paramètres du rendement.

Introduction

Common bacterial blight (CBB), caused by *Xanthomonas axonopodis* pv. *phaseoli* (Smith) Vauterin et al. (*Xap*) [syn. *X. campestris* pv. *phaseoli* (E.F. Smith) Dowson], is the most widespread foliar disease of dry bean (*Phaseolus vulgaris* L.) in Manitoba (Conner et al. 2011; Kim et al. 2017) and in many of the bean growing regions of the world (Coyne and Schuster 1974; Miklas et al. 2006). Seed-borne transmission of *Xap* is entirely responsible for the carryover and spread of CBB in beans in Manitoba, as the pathogen cannot survive on infected plant debris during the cold winters (Wallen and Galway 1979; Bailey et al. 2003). Symptoms of infection by *Xap* usually first appear as water-soaked lesions on the leaves and pods that eventually turn brown and are surrounded by small haloes of chlorotic tissue (Schwartz et al. 2005). In navy beans, pod infection often leads to internal and external infection of the developing seeds (Cafati and Saettler 1980), sometimes resulting in a yellowish discoloration of the seed coat (Boersma et al. 2015). The extent of yield losses can vary depending on weather conditions and the host cultivar, but it can range as high as 25%–40% (Scott and Michaels 1992; Singh and Muñoz 1999; Gillard et al. 2009; Boersma et al. 2015). Options for controlling CBB are limited. Copper-based bactericides are not always effective in reducing the spread and severity of CBB (Singh and Muñoz 1999; Harveson 2019). Treatment of the seed with antibiotics like streptomycin sulfate for CBB control was recently phased out in Canada (Bett and Banniza 2014). The importation of disease-free seed from the relatively dry regions of the US is effective in reducing losses by CBB (Wallen and Galway 1979) but it can be costly (Gillard et al. 2009).

In recent years, the development of CBB-resistant cultivars has provided a new option for controlling the disease. Resistance derived from tepary bean (*Phaseolus acutifolius* A. Gray) is generally considered the most economical and environmentally sustainable way to manage CBB (Singh and Muñoz 1999; Gillard et al. 2009; Shi et al. 2011; Boersma et al. 2015). New dry bean cultivars that carry CBB resistance have been developed for a number of market classes (Michaels et al. 2006; Hou et al. 2011; Osorno et al. 2013; Bett et al. 2014; Balasubramanian et al. 2015; Kelly et al. 2018); however, most dry bean cultivars currently grown in Canada are highly susceptible to CBB and not all resistant dry bean cultivars, and germplasm lines are equally effective in reducing losses in seed yield and quality (Gillard et al. 2009; Boersma et al. 2015; Miklas et al. 2017). The benefits of planting the seed of CBB-resistant cultivars on subsequent bean crops have not been reported.

Seed hydration, also known as seed priming, has been used in a number of crops to improve the uniformity of seed germination and plant stand (Abebe and Modi 2009), but the effects on the agronomic performance of the crops were often inconsistent and usually most evident in dry soils (Kibite and Harker 1991). Seed hydration has been used by Manitoba bean producers to reduce seed breakage (Lange and Brolley 2002) and to ensure more uniform seedling emergence and plant stand (Bennet and Waters 1984). Often the bean seed is soaked in water for only 20–30 min directly before seeding (Lange and Brolley 2002). Concerns have been raised that seed hydration may increase seed-borne transmission of CBB, but there have been no published reports on the effects of seed hydration on seed-to-seedling transmission of CBB.

This study was undertaken to compare the effects of seed-borne and spray applications of *X. axonopodis* pv. *phaseoli* on CBB development in dry bean lines and cultivars with different levels of disease resistance and their impact on yield and yield components. This investigation provides new information on how resistance affects seed-borne transmission of CBB to subsequent crops of the same cultivar. It also furnishes new information on how seed hydration affects the subsequent development of CBB in resistant and susceptible navy beans. Most studies on the effects of CBB resistance on yield and seed quality have been based on the spray application of pathogen inoculum onto the leaves of bean plants that were grown from disease-free seed. In this study, disease development, yield, and seed quality in navy bean crops that were grown from either disease-free seed or infected seed with or without *Xap* spray application were compared. This study also provides information on how the various yield components in resistant and susceptible beans are affected by CBB.

Materials and Methods

Field trials were established at the Morden Research and Development Centre, MB, Canada, (49°11′N and 98°5′W) from 2015 to 2018. Each year, the field site was within 300 m of the weather station that collected the meteorological data for this study. Throughout the 4 yr field study, cereal crops were grown on each of the field sites in the year prior to the CBB experiment. Each year, herbicide and fertilizer applications were made to maximize bean seed yield (Saskatchewan Pulse Growers 2000). The four-row plots measured 5.0 m in length with 0.3 m row spacings, and each bean plot was surrounded by four rows (0.8 m) of soybean [*Glycine max* (L.) Merr.] to minimize the spread of CBB among bean plots. The experiment was arranged in a split-plot design with five main disease infection treatments [i.e., clean (healthy) or diseased-seed with an *Xap* spray or no spray and hydrated diseased seed] as the main-plot treatments. The subplot treatments included the CBB-susceptible dry bean cultivars Envoy and Navigator and five other dry bean genotypes with various degrees of resistance [i.e., OAC Rex (Michaels et al. 2006), HR45 (Park and Dhanvantari 1994), Portage (Hou et al. 2011), and the breeding lines 196-1-4 and H83-21]. The two breeding lines were developed at the Morden Research and Development Centre; line 196-1-4 was derived from a cross of LRS92-1/OAC Rex, and H83-21 arose from the cross Kippen////HR67*2//Envoy/Sel 1308. A preliminary field study (Conner unpublished data) at Morden in 2014 indicated that the line 196-1-4 expressed a level of CBB resistance similar to the highly resistant line HR45 and the cultivar OAC Rex (Gillard et al. 2009; Boersma et al. 2015). The navy bean line H83-21 had an incidence of CBB leaf infection that was greater than that of HR45 but similar to that of OAC Rex. The navy bean cultivar Portage was not included in the preliminary study (Hou et al. 2011), but a previous study indicated it was highly resistant to CBB. All the treatments had six replications. Each year, the plots were seeded in mid-May.

Each year, seed for the clean-seed and the clean-seed *Xap* treatments were obtained from plants of each dry bean cultivar or line that had been grown under disease-free conditions in a greenhouse at Morden. The seed for the diseased-seed, diseased-seed *Xap* spray, and the hydrated-seed treatments were obtained from plots at Morden that had been planted with *Xap*-infected seed and sprayed with a suspension of *Xap* in the previous year. The seed for the seed-hydration treatment were soaked for 15 min in room temperature tap water just prior to seeding. After soaking, the seed were transferred onto paper towels, and the surface of the seed was blotted dry. Testing with a Labtronics model 919 grain moisture meter (Dimo's Tool and Dye/Labtronics®, Winnipeg, MB, Canada) indicated that the seed moisture content was increased from approximately 11% to 17% with seed hydration. Each year just prior to seeding, germination rates of the seeds in each treatment of each dry bean genotype were determined. A seeding rate of 68 viable seeds per row or 45 viable seeds·m^{-2} was used for each of the four-row plots.

The fungicide Headline (pyraclostrobin BASF Canada, Mississauga, ON, Canada) was applied in 2017 and 2018 to minimize the development of anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magnus) Briosi & Cavara], while Lance (boscalid, BASF Canada), was sprayed each year to prevent white mould [*Sclerotinia sclerotiorum* (Lib.) de Bary] at the recommended rates in mid-July and (or) early August.

Cultures of four isolates of *X. axonopodis* pv. *phaseoli* (Gillard et al. 2009) were grown on 15 cm diameter Petri dishes containing potato dextrose agar at room temperature and under ambient light. The 3-d-old cultures of *X. axonopodis* pv. *phaseoli* were scraped with a sterile glass slide and diluted with sterile water to create a stock solution concentration that was standardized at a colorimetric absorbance reading of 310 Klett units. The surfactant Sylgard 309 (Dow Corning Inc., Midland, MI, USA) was added at a rate of 0.2% of water volume. Equal volumes of the four isolates of *X. axonopodis* pv. *phaseoli* (Gillard et al. 2009; Boersma et al. 2015) were combined and applied to the *Xap* spray treatment plots in the latter half of July when the bean plants were just starting to form pods [growth stage R7 (Schwartz et al. 2005)]. Just before the plots were sprayed, the stock solution was further diluted at a rate of 30:1 to create a bacterial suspension of 15 Klett units. The bacterial solution was applied with a back-pack sprayer calibrated to apply 75 mL per row for 3 s. The spray applications were made after sunset under calm, rain-free conditions.

Each summer, the plots were visually assessed for CBB symptoms on the leaves and pods. Disease severity based on the size of the lesions (0–5 scale) (Mutlu et al. 2005) and the incidence of foliar infection (i.e., the percentage of leaves with at least one CBB lesion) (Boersma et al. 2015) was recorded in late August; similar pod ratings were made in late-August or early September. A few days prior to harvest, the length of the plots was trimmed back to 5.0 m. At the end of each growing season, the entire plot was harvested with a small-plot combine, and the seed yield was determined.

In addition, five single plants from each plot were selected at random prior to harvest, and they were individually collected and bagged and later assessed for pod number per plant, seeds per plant, seed discoloration (%), and 100-seed weight (g). The data were used to provide information on how the various yield components in beans were affected by CBB development.

Statistical analysis

All of the data from the 4 yr study were combined and analyzed with the statistical programming language GenStat® (Payne 2017). The data were subjected to analysis of variance (ANOVA) using years, replicates, and plots

Fig. 1. Total monthly precipitation during the growing seasons of 2015–2018 at Morden, Manitoba, shown with the mean precipitation from 1999 to 2019.

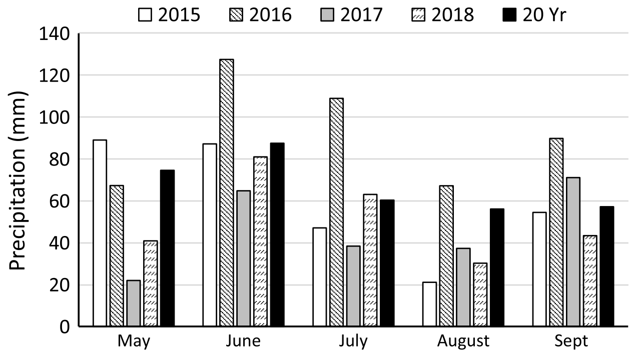
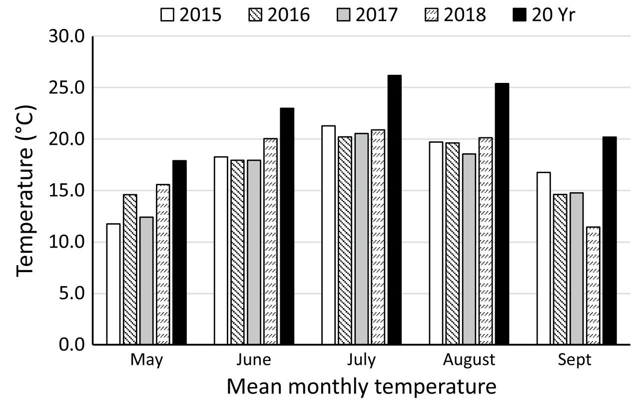


Fig. 2. Mean monthly temperatures during the growing seasons of 2015–2018 at Morden, Manitoba, shown with the mean temperatures from 1999 to 2019.



as random effects in the model with year, cultivars and (or) lines, and disease infection treatments as fixed effects. The underlying assumptions for the ANOVA were checked graphically by plotting the residuals against fitted values for homoscedasticity of variance and against the normal deviate for normality. Outliers for individual plot values greater than three standard deviations were identified and their plots set as missing values. Data on the incidence of leaf infection were measured as a percentage and were converted to angles using the arcsine square root transformation. A square root transformation was used for data on the numbers of pods per plant, number of seeds per plant, and seed weight. No transformation was required for ratings of CBB severity (0–5) or for yield ($t \cdot ha^{-1}$). Differences among cultivars and (or) lines at each field site were compared by least significant differences at $P \leq 0.05$. Statistical differences among growing seasons and their interactions with cultivars and (or) lines and (or) treatments were set at $P \leq 0.05$.

Results

Weather conditions

Weather conditions, especially precipitation, varied greatly during the 4 yr of this field study (Figs. 1 and 2). Average temperatures in each month of the field study were lower than the 20 yr mean (i.e., 1999–2019) (Fig. 2). In 2015 and 2016, total precipitation for May was near the long-term average, but it was much lower in 2017–2018 (Fig. 1). In June, the total precipitation was near the long-term average in 2015 and 2018 but was much greater in 2016 and substantially lower in 2017. Growing conditions were dry in July in 2015 and 2017, near normal in 2018, and extremely wet in 2016. The total amount of precipitation received in August was above normal in 2016 and much lower in the other 3 yr. In September, the amount of precipitation received was above average in 2016 and 2017, near the long-term average in 2015, and below average in 2018.

The 20 yr average for total accumulative precipitation from May to September for Morden was 336 mm, which was far less than the total in 2016 (461 mm), but greater than that received in 2015 (299 mm), 2017 (233 mm), and 2018 (258 mm). Seedling emergence was not recorded, but it was observed that the wet weather in 2016 had a detrimental effect on plant stand in some of the plots that year.

Overall analysis of variance

Weather conditions during the growing season appeared to directly influence CBB development and yield attributes in certain cultivars or lines during the 4 yr of the field study. A combined ANOVA of the data from all 4 yr of the study showed the significant effects of season and treatment × season interactions ($P < 0.01$) for many of the disease and yield attributes (Table 1). For that reason, the results from the wet season of 2016 were separated from the other three dry seasons of the study (i.e., 2015, 2017, and 2018).

Cultivar disease ratings, yield components, and yield

Averaged over all treatments, CBB incidence and severity were numerically greater in the moist year than the dry years and that year had lower yield. Due to year-to-year with only two degrees of freedom, the statistical comparison between seasons had limited power to discern overall effects for individual cultivars (Table 2), but interactions of season with treatments and cultivars were significant. Large differences in disease development were observed among cultivars in all 4 yr of the study. Severe lesions of CBB on large percentages of the leaves were seen consistently on the susceptible dry bean cultivars Navigator and Envoy. The resistant line HR45 had only a few small lesions on its leaves in each year of the study regardless of the treatment. By the end of the growing seasons, low levels of CBB were detected in the clean-seed treatment, which likely arose from the spread of disease from adjacent plots (Tables 3 and 4).

Differences among seasons were observed among treatments within cultivars for most attributes (Tables 3 and 4). The severity of CBB was greater in the wet year

Table 1. Significance levels from a combined ANOVA for plant attributes from four seasons (2015–2018).

Source of variation	df	Severity	Incidence	Pod·plant^{-1}	Seed·plant^{-1}	100-seed weight	Yield
Season (dry vs. moist)	1	.	.	*	*	*	.
Residual	2	.	.	.	.	.	.
Blocks	20	—	—	—	—	—	—
Trt	4	**	**	**	**	**	**
Seed (clean vs. infected)	1	*	**	**	**	**	**
Spray (chk vs. spray)	1	**	**	*	10	*	**
Seed × spray	1	*	**	.	.	.	.
Hydration	1	10	*	**	*	10	*
Season × Trt	4	**	*	**	**	**	**
Season × seed	1	.	.	**	**	**	**
Season × spray	1	**	**	.	.	.	.
Season × seed × spray	1	.	.	.	.	.	.
Season × hydration	1	.	.	.	10	.	*
Residual	88	—	—	—	—	—	—
Cv	6	**	**	**	**	**	**
Season × Cv	6	**	**	**	**	**	**
Trt × Cv	24	**	**	**	**	**	**
Seed × Cv	6	**	**	*	**	**	**
Spray × Cv	6	**	**	10	.	.	**
Seed × spray × Cv	6	**	**	.	.	*	10
Hydration × Cv	6	*	**	.	.	.	.
Season × Trt × Cv	24	*	**	**	**	**	**
Season × seed × Cv	6	.	*	**	**	**	**
Season × spray × Cv	6	**	**	10	10	10	.
Season × seed × spray × Cv	6	.	.	**	**	**	.
Season × hydration × Cv	6	.	.	.	.	.	*
Residual	625	—	—	—	—	—	—

Note: df, degree of freedom; Chk, check; Cv, cultivar; trt, treatment. $P < 0.1$, 0.5, and 0.001 are indicated by 10, *, **, respectively (. = $P > 0.10$).

Table 2. The severity and incidence of common bacterial blight symptoms on the leaves and yield components and yield in dry bean genotypes in wet (2016) and dry seasons (2015 and 2017–2018).

Cultivar	Treatment	Severity (0–5)	Incidence (Angle)	Incidence (%)	Pod·plant^{-1} ($\sqrt{n}$)	Pod·plant^{-1} (n)	Seed·plant^{-1} ($\sqrt{n}$)	Seed·plant^{-1} (n)	100-seed weight ($\sqrt{g}$)	100-seed weight (g)	Yield (t·ha^{-1})	Yield Δ(%)
HR45	Dry trials	1.9	6	1	3.7	14	7.7	59	3.6	13	5.38	0
	Moist trial	2.7	8	2	5.4	29	12.5	157	5.9	34	4.97	−8
Portage	Dry trials	1.8	11	3	4.0	16	8.5	72	3.7	14	4.94	0
	Moist trial	3.0	14	6	5.5	31	12.8	163	5.6	31	3.76	−24
196-1-4	Dry trials	2.3	10	3	3.8	15	8.1	66	3.4	11	5.21	0
	Moist trial	3.1	22	14	5.4	29	12.4	153	5.2	27	4.17	−20
H83-21	Dry trials	2.8	21	12	4.0	16	8.2	67	3.6	13	4.86	0
	Moist trial	3.0	19	11	5.0	25	11.3	127	4.8	23	3.90	−20
OAC Rex	Dry trials	2.8	17	8	3.6	13	7.6	58	3.2	10	4.85	0
	Moist trial	3.0	13	5	5.3	29	12.3	152	5.2	27	4.78	−1
Navigator	Dry trials	3.7	41	44	3.6	13	7.6	58	3.3	11	4.62	0
	Moist trial	3.6	48	55	4.8	23	11.2	125	4.7	22	4.27	−8
Envoy	Dry trials	3.8	45	50	4.0	16	8.0	65	3.4	11	4.74	0
	Moist trial	3.7	46	51	5.9	35	12.2	149	5.3	28	3.36	−29
LSD within Cv (2 df 5%)		2.3	16	—	1.1	—	3.5	—	1.2	—	3.12	—

Note: Δ(%) = percentage difference in yield (2 df). LSD, least significant difference; Cv, cultivar; df, degree of freedom.

Table 3. The severity and incidence of common bacterial blight symptoms on the leaves, yield components, and yield in different treatments of dry bean genotypes in the three dry growing seasons (i.e., 2015, 2017, and 2018).

		Severity	Incidence		Pod·plant^{-1}		Seed·plant^{-1}		100-seed weight		Yield		
Cultivar	Treatment	(0–5)	(Angle)	(%)	($\sqrt{n}$)	(n)	($\sqrt{n}$)	(n)	($\sqrt{g}$)	(g)	(t·ha^{-1})	Δ_1(%)	Δ_3(%)
HR45	Clean Seed	1.3	3	0	3.6	13	7.4	55	3.4	11	5.38	0	.
	Seed-Spray	2.4	10	3	3.4	12	7.1	50	3.3	11	5.40	0	.
	Diseased-Seed	1.6	4	0	3.8	14	7.8	60	3.6	13	5.46	1	0
	Dis-Sd-Spray	2.4	10	3	3.7	14	7.7	59	3.5	13	5.19	.	−5
	Hydration	1.8	5	1	4.0	16	8.4	71	4.0	16	5.50	.	1
Portage	Clean Seed	0.2	1	0	3.8	15	7.9	63	3.4	12	5.28	0	.
	Seed-Spray	3.1	23	15	3.7	14	7.8	62	3.4	12	5.04	−4	.
	Diseased-Seed	1.5	4	1	4.2	18	9.0	80	4.0	16	4.90	−7	0
	Dis-Sd-Spray	3.2	22	14	3.8	15	8.3	68	3.7	13	4.81	.	−2
	Hydration	1.1	4	0	4.4	19	9.5	89	4.1	17	4.65	.	−5
196-1-4	Clean Seed	1.8	4	1	3.8	15	8.1	66	3.3	11	5.10	0	.
	Seed-Spray	3.2	17	9	3.7	14	7.7	60	3.2	10	4.91	−4	.
	Diseased-Seed	1.1	3	0	4.0	16	8.5	72	3.6	13	5.41	6	0
	Dis-Sd-Spray	3.3	17	9	3.7	14	8.1	65	3.3	11	5.24	.	−3
	Hydration	2.1	5	1	3.9	15	8.2	68	3.5	12	5.41	.	0
H83-21	Clean Seed	1.7	6	1	3.9	15	8.0	63	3.5	13	4.97	0	.
	Seed-Spray	3.9	46	51	3.8	14	7.8	61	3.4	12	4.77	−4	.
	Diseased-Seed	1.9	6	1	4.0	16	8.2	67	3.6	13	5.12	3	0
	Dis-Sd-Spray	3.7	35	33	4.0	16	8.2	67	3.6	13	4.44	.	−13
	Hydration	2.6	12	4	4.3	18	8.8	77	3.9	15	5.00	.	−2
OAC Rex	Clean Seed	2.1	9	2	3.6	13	7.4	55	3.2	10	4.84	0	.
	Seed-Spray	3.1	25	17	3.7	14	7.9	62	3.4	11	4.69	−3	.
	Diseased-Seed	2.7	12	4	3.6	13	7.6	57	3.2	11	4.88	1	0
	Dis-Sd-Spray	3.2	25	18	3.6	13	7.4	55	3.1	10	4.77	.	−2
	Hydration	2.8	13	5	3.7	14	7.7	59	3.3	11	5.07	.	4
Navigator	Clean Seed	1.7	10	3	3.6	13	7.8	60	3.3	11	5.82	0	.
	Seed-Spray	4.4	62	78	3.3	11	7.2	52	3.0	9	4.65	−20	.
	Diseased Seed	3.4	31	27	3.7	13	7.7	59	3.4	11	4.46	−23	0
	Dis-Sd-Spray	4.5	62	78	3.7	14	7.8	60	3.3	11	3.88	.	−13
	Hydration	4.2	42	44	3.8	14	7.8	61	3.4	11	4.31	.	−3
Envoy	Clean Seed	3.0	17	8	4.3	18	8.6	74	3.6	13	5.30	0	.
	Seed-Spray	4.3	57	71	3.9	15	7.8	61	3.3	11	4.23	−20	.
	Diseased Seed	3.9	38	37	4.0	16	7.9	63	3.3	11	5.04	−5	0
	Dis-Sd-Spray	4.1	60	75	3.9	15	7.7	59	3.2	10	4.30	.	−15
	Hydration	3.9	53	64	4.1	17	8.1	66	3.4	12	4.82	.	−4
SEM within Cv (n = 18 514 df)		0.23	2.2	—	0.12	—	0.29	—	0.13	—	0.16	—	—
LSD (5%)		0.7	6	—	0.3	—	0.8	—	0.4	—	0.44	—	—

Note: Seed-Spray = treatments planted with disease-free seed that later had their canopy sprayed with inoculum of *Xanthomonas axonopodis* pv. *phaseoli*. Dis-Sd-Spray = treatments planted with diseased seed that later had their canopy sprayed with inoculum of *X. axonopodis* pv. *phaseoli*. Hydration = diseased seeds that were briefly soaked in water immediately before seeding. Δ_1(%) and Δ_3(%) = percentage difference in yield relative to the clean-seed and diseased-seed treatments, i.e., treatments 1 and 3, respectively. The percentage yield losses relative to the clean-seed treatment in the Dis-Sd-Spray and the hydration treatments can be determined by adding the Δ_1 value for diseased seed to the Δ_3 value for the Dis-Sd-Spray and the hydration treatments, respectively. SEM, standard error of the mean; CV, cultivar; df, degree of freedom; LSD, least significant difference; . = $P > 0.10$.

(i.e., 2016) for the resistant dry bean cultivar Portage than it was in the three dry years (i.e., 2015, 2017 and 2018) and the incidence of leaf infection was greater in the wet year than the dry years for CBB resistant line 196-1-4. The yield components of pods per plant, seeds per plant, and seed weight were greater in the wet year than the dry years for all the bean lines and cultivars. Seed yield for the diseased treatments in the wet year was reduced by more than 20% than for clean seed; however, overall, no significant differences in yield were observed between the trials in the wet and dry years trials in any of the dry bean genotypes (Table 2).

CBB development in the dry years

In the three dry years, CBB severity and incidence remained low in the clean-seed treatments of all the lines and cultivars, whereas the *Xap* spray treatment of clean and diseased seed significantly increased CBB symptoms in all the entries especially line H83-21 and the susceptible cultivars Navigator and Envoy. The clean-seed treatment had lower CBB severity ratings than the other treatments in the cultivars Portage, Navigator, and Envoy (Table 3). The severity of CBB was highest in the treatments sprayed with a suspension of *Xap* for all cultivars. Within each cultivar, there were no differences in disease severity ratings among the sprayed treatments regardless of whether they had originated from healthy or diseased seed; however, the *Xap* sprayed plots of the resistant lines and cultivars, such as HR45, Portage, 196-14, and OAC Rex, had lower ratings for CBB severity than the same treatments of the susceptible cultivars Navigator and Envoy. The resistant line H83-21 usually had leaf ratings for CBB severity that were intermediate to those of the resistant and susceptible lines and cultivars. The hydration treatment had CBB severity ratings that were significantly less than those of the two *Xap* spray treatments in Portage, 196-1-4, and H83-21. In the dry years, CBB severity was higher in the seed-hydration treatment than the diseased-seed treatment in lines 196-1-4 and H83-21 and the susceptible cultivar Navigator.

In the dry years, the clean-seed treatment consistently had lower incidences of leaf infection than the two treatments that had been sprayed with *Xap*. The incidences of leaf infection in the clean-seed treatment were less than those of the diseased-seed and hydrated-seed treatments only in the susceptible cultivars Navigator and Envoy. The incidence of CBB leaf infection was greater in the seed-hydration treatments than the diseased-seed treatment in the susceptible cultivars Navigator and Envoy. The incidence of leaf infection between the clean- and diseased-seed plots that were sprayed with inoculum of *Xap* was similar in all the cultivars and lines except for line H83-21, in which it was greater in the plots with diseased seed.

CBB development in the wet year

In 2016, no significant differences in the severity rating of CBB on the leaves were evident among the treatments for any of the cultivars (Table 4); however, large differences in the incidences of leaf infection were observed among certain treatments of many of the dry bean lines and cultivars. Ratings for the incidence of leaf infection in the clean-seed treatment were less than the *Xap* spray treatments in the line 196-1-4 and the cultivars Portage, Navigator, and Envoy. The clean-seed treatment only had a lower incidence of leaf infection than the diseased-seed *Xap* spray treatment in line H83-21. No differences in the incidences of leaf infection were observed between the seed-hydration and the diseased-seed treatment in any of the cultivars.

Yield components in the dry years

Treatment effects were observed to significantly reduce pod and seed number in several of the bean entries, while significant minor reductions in seed weight were detected among some of the treatments in a few of the bean lines and cultivars. The number of pods and seeds per plant in the seed-hydration treatment was the greatest or among the greatest of the treatments in all the dry bean lines and cultivars (Table 3). The diseased-seed treatment with no *Xap* spray had pod and seed numbers that were greater than the clean-seed treatment only in the cultivar Portage. Compared with the clean-seed treatment, the number of pods per plant was reduced in the clean-seed *Xap* spray and the diseased-seed *Xap* spray treatments in the cultivar Envoy. The number of seeds per plant in the clean-seed treatment of Envoy was greater than that of the other diseased-seed *Xap* treatment. None of the other treatments within cultivars showed significant differences.

The 100-seed weight was greatest in the seed-hydration treatments in the resistant lines HR45 and H83-21 and the resistant cultivar Portage. The diseased-seed treatment had a greater seed weight than all the treatments except the seed-hydration treatment in the cultivar Portage.

Yield components in the wet year

Differences were evident for most of the yield components of the treatments within certain dry bean lines and cultivars in 2016 (Table 4). The yield components were among the least for the clean-seed treatment. In bean lines HR45 and H83-21, the clean-seed, clean-seed *Xap* spray, and diseased-seed *Xap* spray treatments had low numbers of pods per plant and seeds per plant as well as low seed weight. The clean-seed and clean-seed *Xap* spray treatments in the cultivar Portage had reduced numbers of pods per plant and seeds per plant and low seed weight. In the dry bean line 196-1-4, pod and seed numbers per plant and seed weight were lowest in the clean-seed *Xap* spray treatment and only slightly greater in the clean-seed treatment, which still was less than the diseased-seed *Xap* spray treatment. The number of pods per plant was lower in the clean-seed and the diseased-seed treatments in cultivar OAC Rex than in the seed-hydration treatment. The clean-seed treatment of OAC Rex had lower seed numbers than the diseased-seed *Xap* spray and the seed-hydration treatments. The clean-seed treatment also produced a lower seed weight than all the other treatments for OAC Rex. In Navigator, pod and seed numbers were lower in the clean-seed treatment than the seed-hydration treatment, but all the treatments in Navigator had similar seed weight. In Envoy, the number of seeds and pods per plant, as well as seed weight, were greatest in the seed-hydration treatment and lowest in clean-seed and clean-seed *Xap* spray treatments.

Table 4. The severity and incidence of common bacterial blight symptoms on the leaves and the yield components and yield in different treatments of dry bean genotypes in the wet growing season (i.e., 2016).

		Severity	Incidence		Pod·plant^{-1}		Seed·plant^{-1}		100-seed weight		Yield		
Cultivar	Treatment	(0–5)	(Angle)	(%)	($\sqrt{n}$)	(n)	($\sqrt{n}$)	(n)	($\sqrt{g}$)	(g)	(t·ha^{-1})	Δ_1(%)	Δ_3(%)
HR45	Clean Seed	2.3	6	1	4.9	24	11	126	5.3	28	5.81	0	.
	Seed-Spray	3.0	9	2	4.7	22	11	132	5.5	31	5.41	−7	.
	Diseased Seed	2.3	8	2	5.9	35	13	182	6.4	40	4.66	−20	0
	Dis-Sd-Spray	2.8	9	3	5.0	25	11	131	5.2	27	4.51	.	−3
	Hydration	2.8	9	2	6.5	43	15	228	6.9	48	4.47	.	−4
Portage	Clean Seed	2.8	7	1	4.6	22	11	113	4.8	23	5.10	0	.
	Seed-Spray	3.2	19	10	4.7	22	11	122	4.8	23	4.37	−14	.
	Diseased Seed	3.0	12	4	5.9	35	14	187	6.0	36	3.64	−29	0
	Dis-Sd-Spray	3.0	18	10	6.1	37	14	194	6.1	37	3.08	.	−16
	Hydration	3.0	16	7	6.3	39	15	211	6.2	39	2.64	.	−28
196-1-4	Clean Seed	3.2	11	4	5.2	27	12	146	5.1	26	5.27	0	.
	Seed-Spray	3.2	31	27	4.3	18	10	93	4.0	16	4.66	−12	.
	Diseased Seed	3.0	19	10	5.8	33	13	177	5.6	32	4.59	−13	0
	Dis-Sd-Spray	3.2	30	26	5.9	35	14	190	5.7	33	3.65	.	−21
	Hydration	3.2	18	10	5.6	32	13	171	5.4	29	2.66	.	−42
H83-21	Clean Seed	2.8	13	5	4.4	19	10	99	4.3	19	4.44	0	.
	Seed-Spray	3.0	22	14	4.4	19	10	98	4.2	18	4.00	−10	.
	Diseased Seed	3.2	16	8	5.6	32	13	165	5.6	31	4.11	−7	0
	Dis-Sd-Spray	3.0	31	27	4.8	23	11	115	4.4	20	3.48	.	−15
	Hydration	3.0	13	5	5.7	32	13	167	5.4	30	3.45	.	−16
OAC Rex	Clean Seed	2.8	9	2	4.9	24	11	128	4.8	23	5.47	0	.
	Seed-Spray	3.0	17	8	5.3	28	12	153	5.2	27	5.13	−6	.
	Diseased Seed	3.0	11	3	5.2	28	12	146	5.3	28	5.03	−8	0
	Dis-Sd-Spray	3.0	20	11	5.5	30	13	157	5.3	28	4.07	.	−19
	Hydration	3.0	12	4	5.8	33	13	180	5.6	32	4.18	.	−17
Navigator	Clean Seed	3.2	33	30	4.4	19	10	104	4.5	20	4.85	0	.
	Seed-Spray	4.0	63	80	4.9	24	11	124	4.7	22	3.86	−20	.
	Diseased Seed	3.2	41	43	4.8	23	11	126	4.7	22	4.52	−7	0
	Dis-Sd-Spray	3.8	57	70	4.8	24	11	124	4.6	21	4.02	.	−11
	Hydration	3.7	45	50	5.1	27	12	147	5.1	26	4.11	.	−9
Envoy	Clean Seed	3.3	17	8	5.0	25	10	106	4.6	21	4.17	0	.
	Seed-Spray	4.0	65	82	4.4	19	9	87	3.9	15	3.31	−21	.
	Diseased Seed	3.3	45	50	6.3	39	13	163	5.6	32	3.37	−19	0
	Dis-Sd-Spray	4.0	59	74	6.3	39	13	176	5.7	32	2.78	.	−18
	Hydration	3.7	43	46	7.5	57	15	239	6.7	45	3.17	.	−6
SEM within Cv (n = 6494 df)		0.40	3.5	—	0.22	—	0.50	—	0.22	—	0.276	—	—
LSD (5%)		1.1	11	—	0.6	—	1.4	—	0.6	—	0.77	—	—

Note: Seed-Spray = treatments planted with disease-free seed that later had their canopy sprayed with inoculum of *Xanthomonas axonopodis* pv. *phaseoli.* Dis-Sd-Spray = treatments planted with diseased seed, which later had their canopy sprayed with inoculum of *X. axonopodis* pv. *phaseoli*. Hydration = diseased seeds that were briefly soaked in water immediately before seeding. Δ_1(%) and Δ_3(%) = percentage difference in yield relative to the clean-seed and diseased-seed treatments, i.e., treatments 1 and 3, respectively. The percentage yield losses relative to the clean-seed treatment in the Dis-Sd-Spray and the hydration treatments can be determined by adding the Δ_1 value for diseased seed to the Δ_3 value for the Dis-Sd-Spray and the Hydration treatments, respectively. SEM, standard error of the mean; CV, cultivar; df, degree of freedom; LSD, least significant difference; . = $P > 0.10$.

Yield in the dry and wet years

In the dry years, the effects of treatments on yield were most evident in the susceptible cultivars, but minor differences in yield also occurred among the CBB-resistant cultivar and lines (i.e., Portage, 196-1-4, and H83-1). There were no effects of treatment on yields of HR45 and OAC Rex. The clean-seed produced a greater yield than both of the *Xap* spray treatments in the susceptible cultivars Navigator and Envoy. Losses in these two cultivars associated with the *Xap* spray ranged from 20%–36% (Table 3). The clean-seed treatment in the resistant cultivar Portage out-yielded the diseased-seed *Xap* spray and the seed-hydration treatments by 7% and 12%, respectively. Yield in the seed-hydration treatment was greatest or among the greatest of the treatments in lines 196-1-4 and H83-21. The diseased-seed *Xap* spray treatment of line H83-21 had a 11%–13% lower yield than the hydration treatment and the diseased-seed treatment, respectively. No yield differences were detected among the treatments within the resistant line HR45 and cultivar OAC Rex.

Under the relatively wet conditions in 2016, more differences in yield were observed among the treatments within the lines and cultivars than in the dry years (Tables 3 and 4). The impact of CBB on seed yield was greater in 2016 than in the dryer years of this study, and differences in yield were detected among certain treatments in all the dry bean lines and cultivars (Table 4). In all the bean lines and cultivars, seed yield was greatest in the clean-seed treatment.

In the wet growing season, the seed yield of the clean-seed *Xap* spray treatment in the CBB resistant line HR45 and resistant cultivar Portage was greater than that of all the other treatments except the clean-seed and the diseased-seed treatments. The yield of the diseased-seed treatment was intermediate to the other treatments and 20% less than the clean-seed treatment in HR45 and 29% less in Portage. In the resistant line 196-1-4, seed yield was higher in the clean-seed, clean-seed *Xap* spray, and the diseased-seed treatments than in the diseased-seed *Xap* spray and the hydration treatments. Compared with the clean-seed treatment of line 196-1-4, seed yield was 34% and 55% less in the diseased-seed *Xap* spray and the hydration treatments, respectively. The yield of the hydration treatment also was lower than that of the diseased-seed *Xap* spray treatment. In the resistant line H83-21 and the resistant cultivar OAC Rex, the yield of the clean-seed treatment was greater than that of the diseased-seed *Xap* spray and the hydration treatments. The seed yields of the clean-seed *Xap* spray and diseased-seed treatments were intermediate to the other treatments in H83-21, while in OAC Rex they were not different from the clean-seed treatment.

In contrast to the dry years, significant treatment effects on yield were detected in each of the lines and cultivars in the wet year of 2016. The yields of the clean-seed *Xap* spray and the diseased-seed *Xap* spray treatments of the CBB-susceptible cultivar Navigator were less than that of the clean-seed treatment, while the diseased-seed and hydration treatments produced yields that were intermediate to the other treatments. The yields of the clean-seed *Xap* spray and the diseased-seed treatments were 20% and 18% less than that of the clean-seed treatment of Navigator, respectively. In the susceptible cultivar Envoy, yield was greater in the clean-seed treatment than in all the other treatments. Compared with the clean-seed treatment, the other treatments suffered losses in yield that ranged from 19% to 37%.

Each year, the seeds in the 100-seed weight samples were examined for yellowing and discoloration caused by CBB infection. Similarly, the plots were assessed each year for the incidence and severity of CBB symptoms on the pods at the end of the growing season; however, the incidence of seed discoloration and pod infection was low in all the plots in each year of the study (data not shown).

Discussion

CBB continues to be the most prevalent foliar disease of dry bean in Manitoba (Kim et al. 2017, 2019). This study clearly demonstrated that the differences in the incidence of leaf infection and severity of CBB between resistant lines and cultivars and susceptible cultivars of dry beans remained consistent under a wide range of growing conditions. As previously reported (Gillard et al. 2009; Boersma et al. 2015), the susceptible navy bean cultivars Navigator and Envoy always had high severity ratings and incidences of leaf infection, even in the dry growing seasons. The severity and incidence of CBB leaf symptoms was substantially lower in the resistant bean lines and cultivars than the susceptible cultivars, but the relative ranking amongst the resistant lines and cultivars varied slightly between the wet and dry growing seasons.

This study was the first one to examine the effects of seed hydration on CBB development in dry beans. During the dry growing seasons, the incidence of leaf infection was greater in the hydrated-seed treatment than the diseased-seed treatment of the susceptible cultivars Navigator and Envoy; however, no differences in CBB ratings were observed among those treatments in the resistant lines and cultivars. In the wet growing season, no differences in CBB severity or incidence of leaf infection between the hydrated-seed and the diseased-seed treatments were observed in any of the dry bean lines and cultivars. Possibly the relatively wet soil conditions during the 2016 growing season offset any effect of the seed-hydration treatment on CBB development in the susceptible bean cultivars. Kibite and Harker (1991) also reported that the effects of seed hydration on the agronomic performance of cereal crops were most apparent under dry conditions.

The s1eed-hydration treatment did not improve seed yields in any of the dry bean cultivars or lines compared with the diseased-seed treatment. In fact, in the wet growing season, seed yield was lower in the seed-hydration treatment than in the diseased-seed treatment in the CBB resistant line 196-1-4 and the cultivars Portage and OAC Rex. These results demonstrate that seed hydration may enhance the severity of leaf diseases such as CBB and reduce yield. Ghassemi-Golezani et al. (2010)

reported that hydro-priming of pinto bean seed enhanced seed germination and seedling vigor, but it did not improve yield or seed weight. Bennet and Waters (1984) observed that increases in seed moisture content above 8%–10% resulted in greater seedling emergence and plant stands of lima bean (*Phaseolus lunatus* L.) but did not consistently improve seed yield. It is possible that different lengths of exposure to the seed soaking process used for seed hydration might lead to different results on CBB leaf symptom development and yield of dry beans, but the results of this study indicate that seed hydration did not produce any beneficial effects.

The seed yields of the dry bean lines and cultivars were consistently lower under wet conditions that occurred in 2016 than in the other 3 yr of the study. Wet conditions favor CBB incidence and severity (Bailey et al. 2003; Schwartz et al. 2005), but there was not a significant difference in CBB development within bean genotypes between growing seasons. The reductions in yield for some genotypes in 2016 did not appear to be entirely due to CBB. A survey of diseases of commercial fields of dry beans in Manitoba in 2016, Kim et al. (2017) noted that areas in certain fields had drowned out, and *Fusarium* root rot was much more severe than it had been in previous years. It is likely that the adverse growing conditions and possibly root diseases also contributed to the lower yields in 2016.

During the dry and wet growing seasons, a comparison between the clean-seed and diseased-seed treatments showed no difference in CBB severity or incidence of leaf infection in the resistant dry bean lines and cultivars; however, the severity and incidence of CBB leaf infection in the diseased-seed treatment was greater than that of the clean-seed treatment for Envoy in all 4 yr of the study, but this treatment difference was only apparent in Navigator in the dry growing seasons.

In the wet growing season, differences in yield between the clean-seed and diseased-seed treatments were observed in HR45, Portage, and Envoy. With the exception of Envoy in the wet growing season, the differences in yield between those treatments did not appear to be directly related to differences in CBB severity. In the dry growing season, yield differences between the clean-seed and diseased-seed treatments only occurred in the cultivar Navigator.

Cafati and Saettler (1980) demonstrated that systemic infection of the vascular system into the pods could result in internal infection of symptomless seeds of the resistant tepary bean Arizona-Buff, but the populations of *Xap* internally colonizing the seed were much lower in tepary beans than they were in the susceptible dry bean cultivars. A field study by Mabagala (1997) confirmed that systemic infection by the CBB pathogen can occur in symptomless seeds of resistant cultivars, so a concern was raised that infected seed of resistant cultivars could spread the disease into new areas of the USA where winter conditions were mild enough to permit the survival of the pathogen. In the bean growing regions of Canada, however, infected seed of resistant or susceptible cultivars will not promote further spread of CBB because the harsh winters do not permit the survival of *Xap* on crop debris (Wallen and Galway 1979; Bailey et al. 2003). In the current study, decreases in the spread of CBB within the crop canopy and onto the seeds of resistant cultivars resulted in only a low incidence of seed infection, which should reduce any subsequent transmission of *Xap* to the seedlings. The results of the current study indicate that dry bean cultivars with high levels of CBB resistance do not require the planting of healthy seed each year to prevent outbreaks of this disease. For many years in Canada, the importation of healthy seed from the dryer growing regions of the USA has been a strategy to reduce the risk of outbreaks of CBB in susceptible cultivars, but bean producers must pay a premium for that seed (Gillard et al. 2009). The severity and incidence of CBB remained low in the disease-seed treatment of all the resistant lines and cultivars throughout the current field study. This showed that only low rates of disease transmission occurred in the resistant lines and cultivars regardless of the amount of precipitation received in which the year the seed of developed. These results indicate that even in wet years, the production of resistant lines and cultivars will not result in severe outbreaks of CBB in subsequent bean crops. The availability of CBB-resistant cultivars of dry beans will reduce or eliminate the need to import healthy seed to control that disease and should promote greater seed production in Canada.

In the dry seasons of the current study, seed yield losses in treatments in the susceptible cultivars Navigator and Envoy ranged as high as 36% and 20%, respectively. In the wet year of this study, losses in seed yield in Navigator and Envoy were as high as 20% and 37%, respectively. Throughout the study, the combination of diseased seed and a *Xap* spray for the two susceptible cultivars always resulted in the most severe losses in seed yield. Losses in seed yield for the two susceptible cultivars from diseased seed alone were 23% in Navigator and 5% for Envoy in the dry season, and 7% for Navigator and 19% in Envoy in the wet year. In the dry years of the study, the yield of the diseased-seed treatment for both susceptible cultivars were always greater than that of the diseased-seed plus *Xap* spray treatment. In the wet year, however, the yields in the diseased-seed treatment were not different from those in the diseased-seed plus *Xap* spray treatment. These results indicate that under dry environmental conditions, the combination of diseased-seed and a *Xap* spray treatment may overestimate the impact of CBB on yield. The diseased-seed treatment most closely corresponds with the natural conditions that occur in a grower's field, so it seems to provide a more realistic estimate of the deleterious effects of CBB on seed yield. Based on these observations, it appears that future studies on the impact of various treatments on yield losses caused by CBB should use only diseased seed as the source of infection.

As observed in previous studies (Gillard et al. 2009; Boersma et al. 2015; Miklas et al. 2017), not all sources of CBB resistance were equally effective in reducing seed yield losses. This is not surprising, since multiple loci can influence the degree of resistance of dry beans to CBB (Yu et al. 2012; Boersma et al. 2015). Under dry growing conditions, no losses in yield occurred in the highly resistant cultivars HR45 and OAC Rex; however, differences in yield were observed among treatments of each of the other dry bean cultivars or lines. The clean-seed treatment was always one of the highest yielding treatments in each of the dry bean cultivars or lines. This confirms past observations that the use of disease-free seed is an effective method for reducing yield losses caused by CBB in susceptible cultivars (Schwartz et al. 2005). Miklas et al. (2017) noted that CBB resistance did not result in a beneficial effect on yield under moderate CBB pressure, but it did stabilize yields when environmental conditions favored severe disease development in susceptible genotypes.

In the current study, there were not always clear relationships between reductions in seed yield components and yield loss among the treatments in the dry bean lines and cultivars. In the dry growing seasons of the current study, the seed-hydration treatment of the resistant dry bean cultivar HR45 increased all the yield components but did not result in greater seed yield than the other treatments. In the resistant cultivar Portage, the diseased-seed treatment had the greatest number of pods and seed per plant, as well as the highest seed weight, but seed yield was greatest in the clean-seed treatment. In the resistant line 196-1-4, the only yield component affected by the treatments was the number of seeds per plant, which was associated with greater yields in the clean-seed, diseased-seed, and hydration treatments in comparison with the clean-seed *Xap* spray treatment. In the resistant line H83-21, all the yield components were affected by the treatments, but they did not completely account for the higher seed yields in the clean-seed, diseased-seed, and hydrated-seed treatments than the diseased-seed *Xap* spray treatment. In the resistant cultivar OAC Rex, no differences in seed yield or the yield components were detected among any of the treatments. Only the number of pods per plant in the cultivar Navigator differed among the treatments, but differences in the numbers of pods were not directly related to the lower yields in some treatments. In Envoy, the two *Xap* spray treatments had fewer pods per plant and a lower number of seeds per plant than the clean-seed treatment, which resulted in lower yields in those treatments. In the wet year 2016, yields were greatest in the clean-seed treatment of all the dry bean lines and cultivars, but the values for its yield components were always among the lowest of the infection treatments.

In a field study of recombinant inbred lines in Ontario, Tar'an et al. (2001) reported that the number of pods per plant was reduced by CBB, but there were no effects on number of seed per pod or seed weight; however, in that study, CBB reduced seed yield only by 6%. A study by Wallen and Jackson (1975) in Ontario determined that CBB was responsible for seed yield losses that ranged between 37% and 40%. In the same study, reductions in seed weight ranged from 10.6% to 17.8% and were attributed to early defoliation caused by CBB. In a field study that compared different sources of *Xap* inocula, Fininsa and Tefera (2001) reported that large differences in seed yield among treatments were not associated with any differences in seed weight, number of pods per plant, or number of seeds per plant among those same treatments. Miklas et al. (2017) determined that the quantitative trait loci *BC420* and *SU91* for CBB resistance were able to prevent losses in seed weight only under severe disease pressure.

In the wet year, the treatments differentially affected all the seed components except for seed weight in Navigator. None of the differences in the yield components in the treatments of any of the dry bean cultivars were directly associated with the high yield in the clean-seed treatment; however, for all of growing seasons, the greater yield in the clean-seed treatment of each of the dry bean cultivars and lines was consistently associated with low ratings for CBB severity and incidence of leaf infection. None of the infection treatments affected yield in the highly resistant cultivars HR45 or OAC Rex in the dry growing seasons, but treatment differences were evident in the wet growing season when conditions were more conducive for CBB development. The severity and incidence of CBB leaf infection in the other resistant lines and cultivars in the wet and dry growing seasons were sufficient to cause slight reductions in yields, as has been observed in other studies of CBB-resistant lines and cultivars (Gillard et al. 2009; Boersma et al. 2015). Yet in all growing seasons, the resistance in those lines and cultivars was sufficient to minimize the magnitude of yield loss from that observed among the infection treatments in the susceptible dry bean cultivars Navigator and Envoy.

In a fungicide study on the control of angular leaf spot [*Pseudocercospora griseola* (Sacc.) Crous & Braun] of dry beans in Tanzania, Mongi et al. (2018) demonstrated that the yield components of various treatments were strongly influenced by the amount of rain received during the growing season because of its influence on disease development. Habtu and Zadoks (1995) speculated that the effect of bean rust [*Uromyces appendiculatus* (Pers.) Link] on yield components varied with climatic conditions, cultivars, and the host–parasite interaction. In the current study, weather conditions affected CBB development and yield, but it did not account for the differences in the yield components among infection treatments within cultivars.

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In a study of root rot of beans caused by *Rhizoctonia solani* Kühn, van Bruggen and Arneson (1986) showed that the various yield components could compensate for each other depending on disease development and weather conditions at different growth stages of the crop. The results of the current study do not indicate that compensation occurred among any of the yield components. They also demonstrated that reductions in number of plants per row could be offset by increases in the other yield components. In the current study, adjustments in seeding rates were made to compensate for differences in seed germination, and plant stands generally appeared quite uniform in the dry growing seasons; however, slight differences in plant numbers may have accounted for the inconsistencies in the relationship between the yield components and the yields of treatments within the cultivars especially in the wet year.

This field study was undertaken to determine the benefits of growing CBB-resistant dry bean lines and cultivars under a range of environmental conditions in Manitoba. The magnitude of the differences of the effects of wet and dry growing conditions on CBB symptom development and yield in resistant and susceptible dry beans was greater than expected. The Ontario line and cultivar HR45 and OAC Rex provided better control of CBB than the resistant cultivar and lines developed for production in Manitoba. Among the Manitoba dry bean entries, CBB most adversely affected the yields of line 196-1-4; however, the yield loss in navy bean lines H83-21 and the cultivar Portage remained low throughout the 4 yr study regardless of exposure to seed-borne or foliar-applied inocula of *Xap* and the weather conditions in the year of the study or in the previous year when the seed was produced. The dry bean line H83-21 and the cultivar Portage have the advantage that they were selected for their adaption and productivity under normal growing conditions in the bean producing region of southern Manitoba. Based on their performance in the current study, they should be effective in preventing future CBB outbreaks in this region.

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