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Snap bean response to pyroxasulfone in a diversity panel

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Research Article

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Abstract

If available for use on snap bean, pyroxasulfone would provide valuable preemergence control of troublesome weed species that currently contaminate the crop postharvest. The extent to which snap bean tolerates pyroxasulfone is poorly documented. The objective of this research was to quantify the extent to which pyroxasulfone tolerance exists in a large collection of snap bean cultivars. A snap bean diversity panel of 277 entries was screened for tolerance to sulfentrazone at a rate of 420 g ai ha^{-1} in a field trial in 2019 and 2020 near Urbana, IL. Snap bean cultivars exhibited variation in tolerance to pyroxasulfone. While a handful of cultivars were tolerant across variable environments, most cultivars were sensitive in the year that had 30% more water supply (rainfall plus sprinkler irrigation) within 3 wk of planting. Low estimates of broad-sense heritability reflect a large influence of the environment on seedling emergence and growth. With a few exceptions, currently, the margin of crop safety across diverse germplasm is insufficient for registration of pyroxasulfone use on snap bean crops.

Introduction

Vegetable growers in the United States depend on the availability of efficacious weed management tools to maintain profitable production of snap bean. Snap bean grown for the processing market is harvested by machine, and surviving weeds can be stripped of leaves, stems, pods, or berries that comingle with harvested snap bean pods. The processing facility uses several gravity and optical techniques to remove such contamination; however, the cleaning process can slow packing operations to a point at which the cost of removing weeds can exceed the value of the product.

Nightshade species, including hairy nightshade (*Solanum physafolium* Rusby), is problematic because the plant produces toxic berries. Pigweed species, particularly waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer], is problematic because stems break into bean-sized pieces. Both hairy nightshade and waterhemp often escape existing control programs in snap bean crops and their plant parts can elude the sorting process for weed removal (GP, personal communication). Consumers and processors alike have a low tolerance for weedy foreign material in food products.

The foundation of managing nightshade and pigweeds in agronomic crops involves using effective preemergence (PRE) herbicides. Unfortunately, many PRE herbicides with the greatest efficacy against nightshade, pigweeds, and many other summer annual weeds are not registered for use with snap bean crops. Products including dimethenamid, flumioxazin, and sulfentrazone do not have herbicide manufacturer registration support because of concerns of crop sensitivity (Anonymous 2022). Far less is known about snap bean tolerance to pyroxasulfone, a Group 15 herbicide (as categorized by the Weed Science Society of America) that inhibits very long chain fatty acid synthesis (Tanetani et al. 2011). Compared to *S*-metolachlor, which is currently registered for use on snap bean, pyroxasulfone can provide better control of troublesome broadleaf weeds including multiple herbicide-resistant waterhemp (Hausman et al. 2013).

Quantifying snap bean tolerance to pyroxasulfone would provide an understanding of the potential risk of crop injury. Individual studies of crop tolerance to herbicides are often evaluated with a handful of cultivars (e.g., less than five); however, differential herbicide tolerance observed in a small number of entries sheds little light on potential outcomes in a population of cultivars that better represent commercial production. For instance, evaluation of an edamame [*Glycine max* (L.) Merr.] diversity panel ($n > 120$) confirmed that several herbicides used in grain-type soybean were just as safe on edamame grown throughout the United States, facilitating herbicide registrations on the minor crop (Williams and Nelson 2014). Moreover, evaluating herbicide tolerance in a diversity panel with associated genomic data may identify genomic regions related to herbicide tolerance, which could be useful in crop improvement (Saballos et al. 2022). Therefore, the objective of this research was to quantify the extent to which pyroxasulfone tolerance exists in a diverse snap bean panel. Moreover, if crop tolerance to pyroxasulfone appeared to be heritable, follow-up research might identify genomic regions conditioning pyroxasulfone tolerance.

Materials and Methods

Germplasm

The SNap bean Association Panel (SNAP) represents a collection of snap bean cultivars grown in the United States over the last century (Hart et al. 2015). They differ in several traits including growth habit (i.e., bush and pole), market type (i.e., fresh and processing), pod sieve class (i.e., two to six, and flat), and seed size (i.e., 8 to 58 g per 100-seed). Cultivars used in the present work are a subset ($n = 277$) of the SNAP panel that also was tested for tolerance to sulfentrazone (Saballos et al. 2022).

Experimental Approach

A field trial was conducted in 2019 and 2020 at the University of Illinois Vegetable Farm near Urbana, IL (40.076274°N, 88.243032°W). A different field was used each year with soybean as the preceding crop. The soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Arguidolls) averaging 3.5% organic matter, pH 5.9. The seedbed was prepared using two passes of a field cultivator with rolling baskets. Planting dates were June 27, 2019, and June 18, 2020.

The experimental design was a strip plot with three replications. Each block consisted of vertical strips of a cultivar treatment factor and horizontal strips of a herbicide treatment factor. The cultivar treatment factor was randomly assigned snap bean entries in single-row (76-cm spacing) plots. The herbicide treatment factor, applied across each cultivar, received either 1) pyroxasulfone (Zidua SC; BASF, Research Triangle Park, NC) at 420 g ai ha^{-1} at planting or 2) a nontreated control. Each cultivar by herbicide subplot was 2.4 m in length planted with 30 seeds to a depth of 2.5 cm. Pyroxasulfone at 420 g ai ha^{-1} represents a 2× field use rate for soybean at the Urbana location. The rate also differentiated pyroxasulfone-susceptible and -tolerant snap bean cultivars in a preliminary dose-response field trial (MW, personal observation). Pyroxasulfone was incorporated into the soil-water solution with rainfall or rainfall plus sprinkler irrigation in 2019 and 2020, respectively. An additional 0.6 cm of water was applied in 2020 to loosen the soil and avoid seedling mortality from soil crusting.

Data Collection

All snap bean seedlings were counted 3 wk after planting (WAP) to determine plant density (PD). Also at 3 WAP, three plants were randomly selected from each subplot and cut at the soil surface. Shoots were dried until constant weight to determine biomass per plant (BP). Because pyroxasulfone appeared to affect both the emergence and growth of the crop, a cumulative measure of snap bean response was determined. Snap bean total plant biomass per square meter (TPB) was calculated by multiplying the number of plants per square meter in the plot by biomass per plant of the plot. The level of tolerance of the cultivars to pyroxasulfone was calculated by expressing the values of the traits in the herbicide-treated plots as a percentage of the values in the nontreated control plots, hereafter identified as PD_{pct}, BP_{pct}, and TPB_{pct}.

Daily rainfall was obtained from a weather station located within 1 km of the experiment (Illinois State Water Survey, Champaign, IL).

Statistical Analysis

Frequency distributions of PD_{pct}, BP_{pct}, and TPB_{pct} were plotted to visualize the complete SNAP response to pyroxasulfone. Response variables PD_{pct}, BP_{pct}, and TPB_{pct} then were subjected to a Box-Cox transformation to improve normality based on the Shapiro-Wilk test. Transformed response variables were analyzed by ANOVA using the *lmer* function in RStudio software (RStudio Team 2022) using the following model:

$$Y_{ijk} = \mu + C_i + Y_j + (CY)_{ij} + B(Y)_{k(j)} + \varepsilon_{ijk} \quad [1]$$

where Y is the trait value of the plot in the k^{th} block in the j^{th} year, with the i^{th} cultivar, μ is the grand mean, C_i is the random main effect of the i^{th} cultivar, Y_j is the random main effect of the j^{th} year, $(CY)_{ij}$ is the random two-way interaction effect between the i^{th} cultivar and the j^{th} year, $B(Y)_{k(j)}$ is the random effect of the k^{th} block nested within the j^{th} year, and ϵ_{ijk} is the random error term associated with plot in the k^{th} block in the j^{th} year with the i^{th} cultivar. All effects were declared significant at $\alpha = 0.05$. Broad-sense heritability was calculated as a function of variance components from the formula above, as described in Holland et al. (2003). Tukey's honestly significant difference mean separation of cultivars for each trait was calculated using the *HSD.test()* function of the AGRICOLAE package in RStudio (RStudio Team 2022) on transformed data. Means of nontransformed data are presented for ease of interpretation.

Results and Discussion

Weather

Water supply through 3 WAP varied between years (Figure 1). The difference was driven largely by the need to apply water to incorporate the herbicide into the soil-water solution in 2020 followed by additional irrigation to avoid seedling mortality from soil crusting. Shortly after both irrigation events in 2020, unexpected rainfall increased total water supply approximately 30% above conditions that occurred in 2019.

Crop Response

Soil conditions in 2019 favored snap bean tolerance to pyroxasulfone at a rate of 420 g ai ha^{-1}. The frequency distribution of PD_{pct} 3 WAP peaked near 100% of the nontreated control (Figure 2A). Similarly, seedling growth was comparable to that of the nontreated control for many cultivars, as evidenced by BP_{pct}. The cumulative measure of snap bean emergence and growth (i.e., TPB_{pct}) was skewed to the right, indicating that few cultivars were completely tolerant to pyroxasulfone.

Crop tolerance observed in 2019 was less common in 2020. All measures of crop response were reduced by pyroxasulfone (Figure 2B). Response variables PD_{pct} and BP_{pct} were further right-skewed, indicating widespread cultivar sensitivity to pyroxasulfone. The cumulative measure of snap bean emergence and growth (i.e., TPB_{pct}) was again heavily skewed to the right, indicating that most cultivars were quite sensitive to the herbicide in 2020. The additional soil moisture near the time of emergence in 2020

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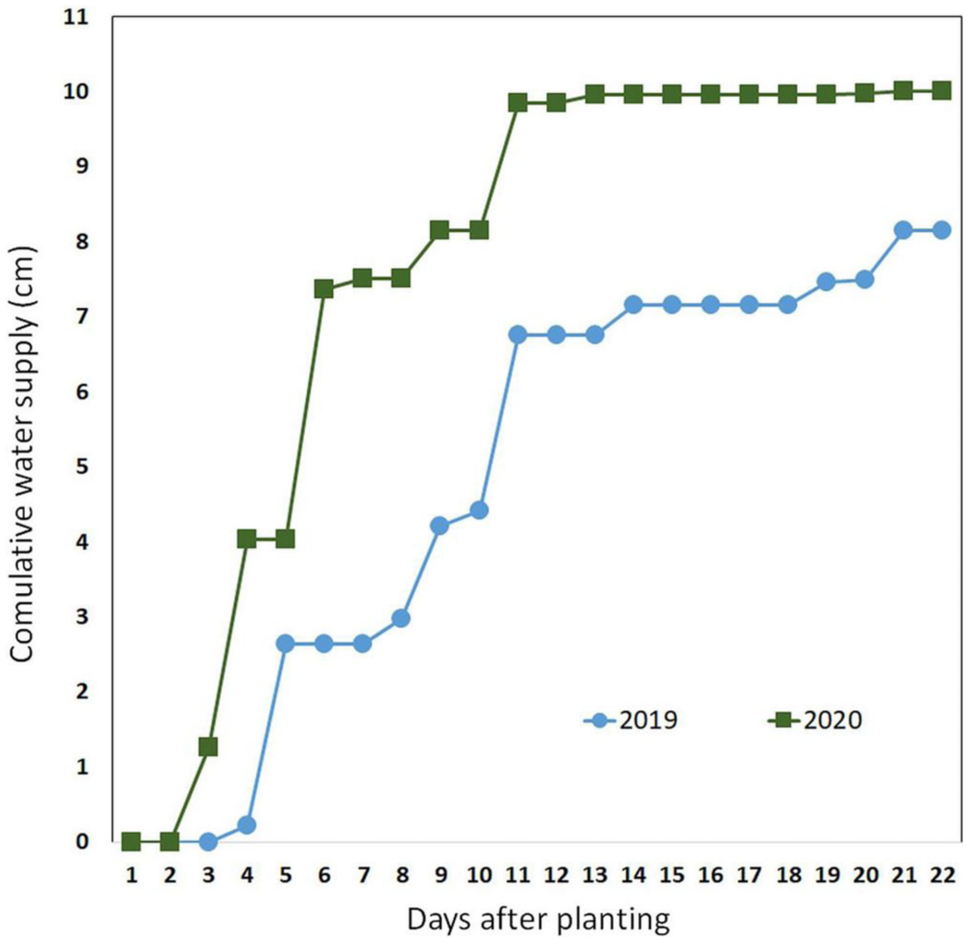

Figure 1. Cumulative water supply (rainfall plus sprinkler irrigation) after planting in field experiments near Urbana, IL, in 2019 and 2020.

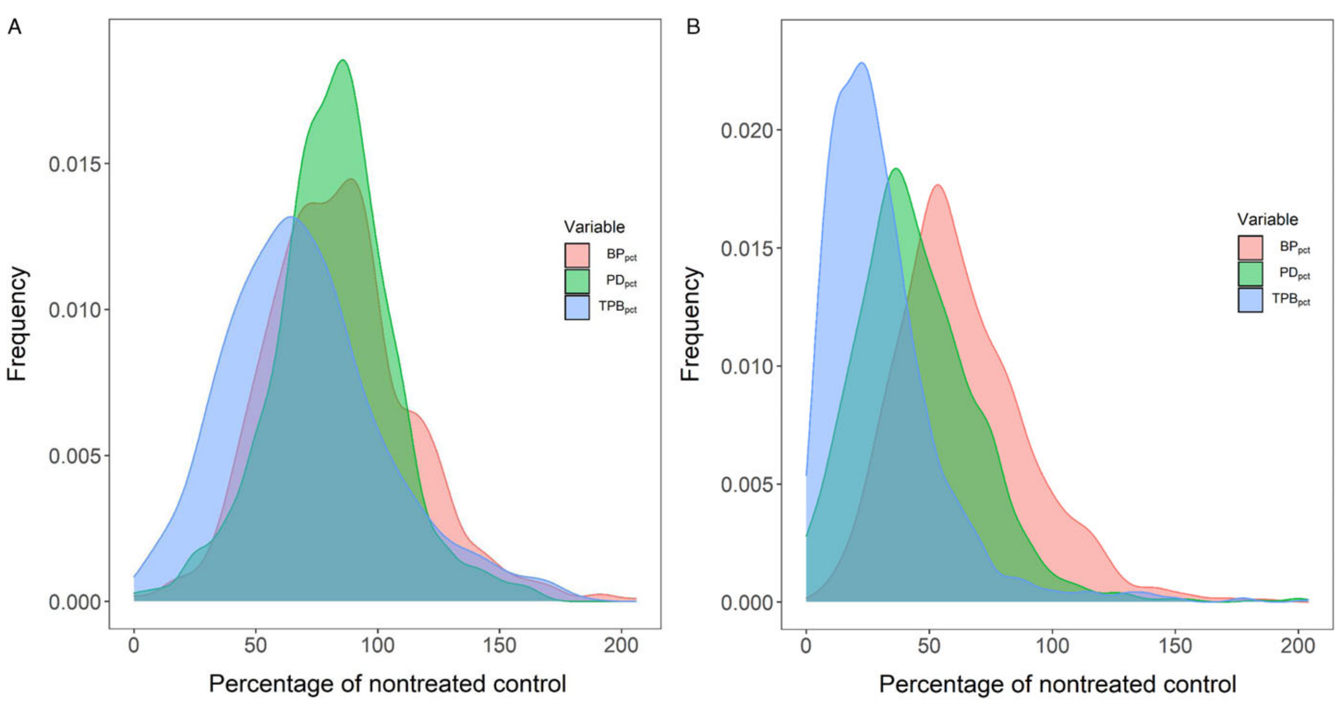

Figure 2. Frequency distributions of snap bean responses (nontransformed) to pyroxasulfone as measured by biomass per plant as a percent of the nontreated control (BP_{pct}), plant density as a percent of the nontreated control (PD_{pct}), and total plant biomass as a percent of the nontreated control (TPB_{pct}) near Urbana, IL, in (A) 2019 and (B) 2020.

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Table 1. Snap bean cultivars listed in the SNAP diversity panel ($n = 277$) most tolerant and most sensitive to pyroxasulfone based on plant density as a percent of the nontreated control.[a,b,c]

Response	Cultivar	PI	Source	Origin	Type	Sieve class	PD_{pct}
							%
Most tolerant	Clyde	PI 583286	USDA	RBSC	processing	2–3	103.5 a
	Eagle	PI 549914	BeanCAP	ASC	dual	5	101.0 ab
	Allure	PI 561587	USDA	SVS	–	2–3	93.6 abc
	Ovation	PI 550142	USDA	RS	processing	4–5	93.4 abc
	Navarro	PI 634725	BeanCAP	HMSC	Romano	flat	93.2 abc
	Minuette	PI 583748	BeanCAP	HMSC	processing	4–5	91.6 abcd
	Carson	PI 634346	BeanCAP	SSI	wax	4	86.6 abcd
	Sentry	PI 550284	USDA	ASC	processing	3–4	85.2 abcd
	Polder	PI 603217	BeanCAP	VSA	processing	3–4	84.4 abcd
	EZ Pick	PI 550255	BeanCAP	NASC	processing	4–5	84.1 abcd
Most sensitive	Bluepak	PI 550259	USDA	RBSC	processing	4–5	42.1 abcd
	Goldrush	PI 549977	BeanCAP	ASC	wax	5	41.9 abcd
	Wax 216	PI 550408	USDA	RNKSC	wax - dual	5	41.4 abcd
	Paloma	–	BeanCAP	NSC	processing	4	38.2 abcd
	Amythest	–	JSS	CHG	fresh market	2–3	38.0 abcd
	Esquire	PI 619196	BeanCAP	SSI	processing	4–5	37.3 abcd
	BBL 156	PI 550403	BeanCAP	RNKSC	processing	4–5	34.5 bcd
	Fury	PI 612597	BeanCAP	SVS	processing	5	33.9 cd
	Blazer	PI 550258	USDA	RBSC	processing	4–5	29.3 cd
	Mount Hood	PI 550251	USDA	FMSC	processing	5	28.0 d

[a]Abbreviations: ASC, Asgrow Seed Company; CHG, Clause Home Garden; FMSC, Ferry-Morse Seed Company; HMSC, Harris Moran Seed Company; NASC, NPI AgService Corporation; NSC, Nunhems Seed Corporation; PD_{pct}, plant density as a percent of the nontreated control; PI, plant introduction number; RBSC, Rogers Brothers Seed Company; RNKSC, Rogers NK Seed Company; RS, Royal Sluis; SNAP, SNap bean Association Panel; SVS, Seminis Vegetable Seeds, Inc.; SSI, Syngenta Seeds Inc.; VSA, Vilmorin, S.A.
[b]Field trials were carried out near Urbana, IL, in 2019 and 2020.
[c]Different letters within a column indicate significantly different means.

likely increased bioavailability and uptake of pyroxasulfone an extent to which fewer cultivars were able to overcome.

Despite differences between years in overall crop response, year did not have an interactive effect on PD_{pct}, BP_{pct}, and TPB_{pct} ($P > 0.076$). However, the main effect of cultivar was highly significant ($P < 0.003$) for measures of crop emergence and seedling growth, demonstrating differential crop response among cultivars.

Snap bean cultivars exhibited variation in tolerance to pyroxasulfone. At 420 g ai ha^{-1} of pyroxasulfone, there were large differences in both crop emergence and seedling growth. Broad-sense heritability of the tolerance estimates were low for PD_{pct} ($H = 19.6$) and BP_{pct} ($H = 17.7$), and no genetic component was detected for TPB_{pct} ($H = 0.0$). The low estimates of broad-sense heritability reflect the large influence of the environment on seedling emergence and growth in the field trials.

Since PD_{pct} had the largest estimated heritability, we used it to rank cultivars from most tolerant to most sensitive across environments. The 10 most tolerant and most sensitive cultivars are shown in Table 1, representing germplasm from 12 different seed companies. While the effect of cultivar was significant for PD_{pct} ($P \leq 0.001$), ranging from 28.0% to 103.5 %, most cultivars had a similar response based on means separation. A few cultivars were consistently among the most tolerant ($PD_{pct} \geq 93.2\%$), including 'Clyde', 'Eagle', 'Allure', 'Ovation', and 'Navarro'. These cultivars represent a range of sieve classes, including flat pods (i.e., Romano), used in processing. Likewise, a few cultivars were consistently among the most sensitive ($PD_{pct} \leq 34.5\%$), including 'BBL 156', 'Fury', 'Blazer', and 'Mount Hood'. These cultivars are in the largest sieve size classes (i.e., 4 and 5) and are used exclusively for processing.

Cultivars also were ranked from most tolerant to most sensitive based on BP_{pct}, which ranged from 40.4% to 114.9% (Table 2). Even though the 10 most tolerant cultivars averaged ≥101.2% BP_{pct} and the 10 most sensitive cultivars averaged ≤52.0% BP_{pct}, means separation failed to differentiate cultivars, a reflection of both variation in the data and using a conservative test statistic for means separation.

An interesting observation is that tolerance based on PD_{pct} is a weak predictor of tolerance measured as BP_{pct}. A post hoc correlation analysis between PD_{pct} and BP_{pct} resulted in a significant yet low correlation coefficient ($\rho = 0.32$). The weak relationship between PD_{pct} and BP_{pct} suggests that genetic mechanisms conditioning response to pyroxasulfone may not be identical for crop emergence and seedling growth.

While primary literature on snap bean response to pyroxasulfone is scant, dry bean response has been evaluated in a few environments. One cultivar each of four market classes of dry bean were tolerant to as much as 200 g ai ha^{-1} of pyroxasulfone on soils ranging from a silty clay loam to a sandy clay loam (Taziar et al. 2016). On relatively sandy soils, minimal crop injury and no yield loss was observed with the application of pyroxasulfone at 209 g ai ha^{-1} on one cultivar each of pinto and small red Mexican dry beans (Sikkema et al. 2008). The margin of crop safety appears thin. Kidney and cranberry dry beans suffered yield loss from pyroxasulfone on Ontario soils, with preplant incorporated applications being more injurious than PRE applications (Soltani et al. 2009). Results of our studies indicate stable tolerance to the herbicide (i.e., consistently high tolerance across environments) is not widespread in the cultivars present in SNAP; however, under favorable conditions the response is comparable to that of field pea (Tidemann et al. 2014), a crop for which pyroxasulfone is registered. Additionally, the evaluation of the diversity panel identified some cultivars that appear to have stable levels of tolerance. These cultivars may represent a source of tolerance alleles for crop improvement.

Snap bean tolerance to pyroxasulfone was evaluated in a diversity panel of 277 snap bean entries. Currently, the margin of crop safety across diverse germplasm is insufficient for registration of pyroxasulfone on snap bean. Large cultivar variability in response to pyroxasulfone was observed, with a handful of cultivars

Table 2. List of snap bean cultivars in the SNAP diversity panel (n = 277) most tolerant and most sensitive to pyroxasulfone based on biomass per plant as a percent of the nontreated control.[a,b,c]

Response	Cultivar	PI	Source	Origin	Type	Sieve class	BP_{pct}
							%
Most tolerant	Fury	PI 612597	BeanCAP	SVS	processing	5	114.9 a
	Miami	PI 549923	USDA	KSC	processing	5	112.3 a
	Benton	PI 550043	BeanCAP	GVS	processing	4–5	111.0 a
	Green Arrow	–	BeanCAP	SVS	–	3–4	106.9 a
	Earlybird	PI 549991	USDA	WPG	processing	5	106.8 a
	Tenderblue	PI 549946	USDA	FMSC	processing	5	102.9 a
	Applause	PI 550344	USDA	ASC	processing	4–5	102.4 a
	Tenderlake	PI 550053	USDA	FMSC	processing	5	102.1 a
	Checkmate	PI 549913	USDA	ASC	processing	4–5	102.0 a
	Cape	PI 549957	USDA	ASC	processing	4–5	101.2 a
Most sensitive	Catania	–	BeanCAP	SVS	processing	2–3	52.0 a
	Balsas	–	BeanCAP	SSI	processing	2–3	50.7 a
	Redon	PI 639240	BeanCAP	SSI	processing	3	49.5 a
	Festina	PI 606782	BeanCAP	SVS	dual	4	49.0 a
	Selecta	–	BeanCAP	SVS	–	2–3	45.7 a
	Esquire	PI 619196	BeanCAP	SSI	processing	4–5	42.1 a
	Booster	–	BeanCAP	SSI	processing	2–3	42.0 a
	Angers	–	BeanCAP	SVS	fresh market	2–3	41.3 a
	Panama	–	BeanCAP	SVS	fresh market	2–3	40.9 a
	Flevoro	PI 561588	USDA	SVS	fresh market	3–4	40.4 a

[a]Abbreviations: ASC, Asgrow Seed Company; BP_{pct}, biomass per plant as a percent of the nontreated control; FMSC, Ferry-Morse Seed Company; GVS, Gallatin Valley Seed Co.; KSC, Keystone Seed Company; PI, plant introduction number; SNAP, SNap bean Association Panel; SSI, Syngenta Seeds Inc.; SVS, Seminis Vegetable Seeds, Inc.; WPG, van Waveren-Pflanzenzucht GmbH.
[b]Field trials were carried out near Urbana, IL, in 2019 and 2020.
[c]Different letters within a column indicate significantly different means.

exhibiting considerable herbicide tolerance even in environmental conditions that severely injured most cultivars. However, most cultivars were sensitive, and a large effect of the environment on crop response may make it difficult to observe relationships between crop phenotype and genotype.

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Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2023.12

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