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Snap bean tolerance to preemergence applications of dimethenamid-P, flumioxazin, lactofen, metribuzin, saflufenacil, and sulfentrazone

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Research Article

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Dimethenamid-P; flumioxazin; lactofen; metribuzin; saflufenacil; sulfentrazone; waterhemp, *Amaranthus tuberculatus* (Moq.) J. D. Sauer; snap bean, *Phaseolus vulgaris* L.

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Abstract

Amaranthus species are problematic weeds in snap bean production systems. They reduce crop yields, and their stem fragments contaminate harvested pods. Knowledge of snap bean tolerance to different preemergence herbicides is limited; however, knowing this tolerance is essential for planning a reliable weed management system, breeding herbicide-tolerant cultivars, and registering herbicides for use on minor crops such as snap bean. Field trials were conducted in 2021 and 2022 to determine the tolerance of eight snap bean cultivars to preemergence herbicides with activity on *Amaranthus* species, including dimethenamid-P, flumioxazin, lactofen, metribuzin, saflufenacil, and sulfentrazone. Snap bean plant density (number of plants per square meter), plant biomass (grams per plant), and canopy biomass (grams per square meter) 21 d after treatment were used to assess crop tolerance to a range of herbicide rates. Linear mixed-effects regression models were fitted to quantify the relationships between preemergence herbicide rate and snap bean cultivar tolerance. Results indicated a high margin of crop safety with dimethenamid-P and lactofen for weed control in snap bean, and a low margin of crop safety with metribuzin and saflufenacil. Results indicated differential cultivar tolerance to flumioxazin and sulfentrazone, which could be driven by genetic variability among cultivars.

Introduction

Snap bean is an important vegetable crop in the United States. The total U.S. production of snap bean in 2022 was 716 million kg, with an average yield of 11,500 kg ha^{-1} (USDA-NASS 2023). Numerous biotic and abiotic factors influence snap bean yield. Among those, weeds cause significant problems in production. Weeds from the *Amaranthus* genus are of particular concern because they affect yield by competing for resources and contaminating harvested pods with fragments of their stems. Aguyoh and Masiunas (2003b) reported that early-emerging redroot pigweed (*Amaranthus retroflexus* L.) could reduce snap bean yields (13% to 58% reduction in yield with 1 to 8 plants m^{-1}), increase harvest difficulties, and contaminate marketable pods. Similar snap bean yield reduction was observed with large crabgrass densities of 1 to 4 plants m^{-1} (Aguyoh and Masiunas 2003a). Stagnari and Pisante (2011) reported reductions in yield of up to 65% on a fresh bean basis due to weed interference throughout the growing season. Growers often use postemergence herbicides to control weeds in snap bean crops. For example, the combination of imazamox and bentazon is commonly used (Blackshaw and Molnar 2008). However, herbicides registered for use on snap bean offer limited control of *Amaranthus* species. Furthermore, due to the paucity of herbicides registered for use on the crop, growers repeatedly apply postemergence herbicides, which facilitates the evolution of herbicide resistance (Evans et al. 2016). Notably, the efficacy of widely used postemergence herbicide glyphosate is declining (Landau et al. 2023).

Several soil-active herbicides applied preemergence have activity on *Amaranthus* species including dimethenamid-P, flumioxazin, lactofen, metribuzin, saflufenacil, and sulfentrazone. Hager et al. (2002) reported that preemergence applications of dimethenamid-P, metribuzin, and sulfentrazone reduced waterhemp densities by 72% at 4 wk after sowing. Hager et al. (2003) reported that a postemergence application of lactofen (218 g ai ha^{-1}) resulted in ≥85% control of waterhemp in soybean 21 d after treatment (DAT). Benoit et al. (2019) found that a premixed formulation of saflufenacil and dimethenamid-P provided 83% waterhemp control at 8 wk after application (WAA) to corn crops. Niekamp and Johnson (2001) showed that flumioxazin and sulfentrazone provided 80% to 90% reduction in waterhemp establishment within 3 WAA. Despite the effectiveness of these herbicides on *Amaranthus* species, these preemergence herbicides are not currently registered for use on snap beans, largely due to insufficient evidence of crop tolerance. Lactofen is currently registered for control of broadleaf weeds in snap bean crops in Oregon and Tennessee (Anonymous 2018); however, information on snap bean safety is required to expand the label.

Limited research has been conducted on snap bean response to preemergence herbicides with activity on *Amaranthus* species. Studies on dry bean may serve as close proxies. Soltani et al. (2011) showed that dry bean was largely tolerant to pendimethalin applied at rates up to 2,160 g ai ha^{-1}. Hekmat et al. (2007) found differential tolerance (7% to 30%) among eight dry bean cultivars when treated with sulfentrazone at 420 and 840 g ai ha^{-1}. Similarly, Urwin et al. (1996) found differential tolerance among 12 dry bean cultivars to EPTC, alachlor, ethalfluralin, and imazethapyr.

Industry support for registering herbicides for use on minor crops such as snap bean requires information on product performance for both weed control and crop safety (Kunkel et al. 2008). Therefore, the objective of this study was to quantify snap bean tolerance to six preemergence herbicides with known activity on *Amaranthus* species; specifically, dimethenamid-P, flumioxazin, lactofen, metribuzin, saflufenacil, and sulfentrazone.

Materials and Methods

Field experiments were conducted in 2021 and 2022 at the University of Illinois Vegetable Crop Farm near Urbana, Illinois (40.08°N, 88.24°W). The soil at the experimental site was classified as a Flanagan silt loam (fine, smectitic, mesic Aquic Arguidolls) with an average of 3.5% organic matter, pH 5.9. Two passes of a field cultivator were used to prepare the seedbed before planting. Planting occurred on June 7, 2021, and May 17, 2022. Daily rainfall and temperature data were obtained from a weather station within 1 km of the experimental sites (Illinois State Weather Survey, Champaign, IL). Growing degree days were calculated using a base temperature of 7 C (Saballos et al. 2022).

Trials were conducted in a split split-plot design with four replications. Six preemergence herbicides (Table 1) and a nontreated control were randomly allocated to main plots that measured 51.2 m by 7.3 m. Three rates of each preemergence herbicide (0.5×, 1×, and 2× the recommended field use rate for soybean) were randomly allocated to subplots that measured 7.3 m by 7.3 m. Eight snap bean cultivars (four commercial cultivars and four controls [two positive controls {i.e., tolerant to sulfentrazone} and two negative controls {i.e., sensitive to sulfentrazone}]) to mimic previous research (Saballos et al. 2022; Table 2) were randomly assigned to sub-subplots. Each sub-subplot was a single 2.4-m row of a specific cultivar. Immediately after seeds were planted to a depth of 2.5 cm, the preemergence herbicides were applied with a CO_2-pressurized backpack sprayer with a 3.0 m boom calibrated to deliver 187 L ha^{-1} at 276 kPa. Herbicides were applied perpendicular to crop rows with a bare soil strip of 3.0 m maintained as a buffer zone between replicates of each treatment factor to mitigate overlap of herbicides. On the day of herbicide application in 2021 the average wind speed was 2.8 km h^{-1}, the average temperature was 24.0 C, and the average soil temperature was 24.7 C at a depth of 2.5 cm. In 2022, the average wind speed was 40 km h^{-1}, average temperature was 20.6 C, and average soil temperature was 21.2 C. Herbicides were incorporated into the soil within 2 d of application by applying 1.0 cm of water with overhead sprinkler irrigation in both years.

Data on snap bean responses were collected 21 DAT. Density of emerged seedlings with actively growing tissue (hereafter called plant density) was recorded for each sub-subplot. Three representative plants per sub-subplot were manually cut at the ground level, dried at 65 C for 24 h, and individual plant biomass was recorded. Canopy biomass was derived as the product of plant density and plant biomass.

All statistical analyses were performed with the R statistical programming language (v.4.3.1; R Core Team 2023). Multivariate analysis of variance was performed with the Satterthwaite method to assess the significance of treatment factors (herbicide, rate, and cultivar) and their interactions at $\alpha = 0.05$. Herbicide, rate, and cultivar were treated as fixed effects, and year and its interactions with other treatment factors were treated as random effects. Marginal and conditional R^2 values were calculated using the MuMIn package (Barton 2012). In addition, each cultivar plant density, plant biomass, and canopy biomass, calculated as a percent of the nontreated control, were regressed against the rate of each herbicide using linear mixed-effect models with the LME4 package (Bates et al. 2015).

Results and Discussion

Total water supply from planting to 14 DAT did not vary between years (average difference of 1.2 cm; Table 3). Collectively, the crop planted in 2021 received more water than it did in 2022; the difference came from a very heavy rain of 11.9 cm at 18 DAT. Interannual weather variation during the critical period of preemergence herbicidal activity (i.e., from the day of application to 14 DAT) was minimal between years. The significance of treatment factors and model structure is given in Table 4.

Snap bean cultivars generally had high tolerance to dimethenamid-P (Figures 1A, 2A, and 3A) and lactofen (Figures 1C, 2C, and 3C) at 21 DAT. The 1× rate of both preemergence herbicides did not inhibit plant density, plant biomass, or canopy biomass, while the 2× rate caused at most a reduction of approximately 25% in plant biomass of all the cultivars. Soltani et al. (2006) reported <5% injury caused by dimethenamid-P at the highest rate of 2,500 g ai ha^{-1} when applied to otebo bean (a market class of dry bean); however, injury was transient and did not affect yield. Industry acceptance of specific herbicides requires the performance of products and minimal crop injury (Wang et al. 2018). These results suggest that dimethenamid-P and lactofen have an acceptable margin of crop safety when applied to snap bean crops.

Differential cultivar response to flumioxazin (Figures 1B, 2B, and 3B) and sulfentrazone (Figures 1F, 2F, and 3F) was observed. Across different snap bean cultivars, 'Navarro' exhibited the greatest tolerance to flumioxazin and sulfentrazone, as evidenced by plant density, plant biomass, and canopy biomass, which were comparable to those of the nontreated control. Various studies reported differential dry bean cultivar tolerance to different preemergence herbicides, including sulfentrazone, acetochlor, S-metolachlor, and imazethapyr (Hekmat et al. 2007; Soltani et al. 2014; Symington et al. 2022; Urwin et al. 1996). Soltani et al. (2005) tested the tolerance of eight dry bean cultivars from four market classes (black, cranberry, kidney, and white bean) to preemergence applications of flumioxazin at three rates (52.7, 70, and 140 g ai ha^{-1})

Table 1. Preemergence herbicides evaluated for snap bean tolerance and recommended use rate on soybean.

Common name	Trade name	Manufacturer	Recommended rate	Mode of action[a]
			g ai ha^{-1}	
Dimethenamid-P	Outlook®	BASF, Charlotte, NC	1,103.4	Very long chain fatty acid synthesis inhibitor
Flumioxazin	Valor EZ®	Valent, San Ramon, CA	105.3	Protoporphyrinogen oxidase inhibitor
Lactofen	Cobra®	Valent U.S.A., San Ramon, CA	332.8	Protoporphyrinogen oxidase inhibitor
Metribuzin	Glory®	ADAMA USA, Raleigh, NC	840.6	Photosystem II inhibitor
Saflufenacil	Sharpen®	BASF, Charlotte, NC	49.9	Protoporphyrinogen oxidase inhibitor
Sulfentrazone	Shutdown®	UPL NA Inc., King of Prussia, PA	429.8	Protoporphyrinogen oxidase inhibitor

[a] According to Weed Science Society of America (2024).

Table 2. Source and 100-seed mass of snap bean cultivars used in field trials in 2021 and 2022 near Urbana, IL.

Cultivar	Source	100-Seed mass
		grams
‘DMC 0488’	Del Monte Corporation, Walnut Creek, CA	22.3
‘Flavor Sweet’	Harris Moran Seed Corporation, Rochester, NY	16.2
‘Goldmine’	Asgrow Seed Company, St. Louis, MO	25.1
‘Navarro’	Harris Moran Seed Company, Rochester, NY	38.6
‘Oregon 5402’	Oregon State University, Corvallis, OR	21.7
‘Oregon 5630’	Oregon State University, Corvallis, OR	22.7
‘Romano 71’	Ferry-Morse Seed Company, Norton, MA	45.6
‘Venture’	Roger Brothers Seed Company, Chicago, IL	26.7

Table 3. Cumulative growing degree days and water supply during the field trials.[a,b,c]

	GDDs		Water supply	
Weeks after planting	2021	2022	2021	2022
1	131	78	5.4	4.6
2	250	176	7.3	5.7
3	356	276	19.2	10.3

[a] Abbreviation: GDDs, growing degree days.

[b] GDD is presented in degrees centigrade; water supply is measured in centimeters.

[c] Herbicides were incorporated into the soil within 2 d of application by applying 1.0 cm of water with overhead sprinkler irrigation both years.

Table 4. Model structure, model fit, and significance of treatment factors and interactions for snap bean plant density, plant biomass, and canopy biomass.

Response variable and model structure	P-value[a]	Model fit	
		R^2 (marginal)	R^2 (conditional)
Plant density[b]	<0.001	0.816	0.861
Herbicide	<0.001		
Rate	<0.001		
Cultivar	<0.001		
Herbicide × rate	<0.001		
Herbicide × cultivar	<0.001		
Cultivar × rate	0.691		
Herbicide × rate × cultivar	<0.001		
Plant biomass[c]	<0.001	0.664	0.705
Herbicide	<0.001		
Rate	<0.001		
Cultivar	<0.001		
Herbicide × rate	<0.001		
Herbicide × cultivar	<0.001		
Cultivar × rate	0.280		
Herbicide × rate × cultivar	0.058		
Canopy biomass[d]	<0.001	0.699	0.756
Herbicide	<0.001		
Rate	<0.001		
Cultivar	<0.001		
Herbicide × rate	<0.001		
Herbicide × cultivar	<0.001		
Cultivar × rate	0.542		
Herbicide × rate × cultivar	0.027		

[a] P-values were calculated with the type III analysis of variance using the Satterthwaite’s method.

[b] Plant density was measured as number of plants per square meter (plants m^{-2}).

[c] Plant biomass was measured as grams per plant (g plant^{-1}).

[d] Canopy biomass was measured as grams per square meter (g m^{-2}).

and found differential tolerance responses among cultivars. Black and white beans showed greater sensitivity, whereas cranberry and kidney beans showed tolerance to preemergence-applied flumioxazin. In the present study, ‘Romano 71’ and ‘Flavor Sweet’ displayed moderate tolerance to sulfentrazone. Cultivars that were most sensitive to sulfentrazone were ‘Oregon 5402’ and ‘DMC 0488’, for which plant density was 43% and 48% of the nontreated control, respectively. In a recent field study, Saballos et al. (2022) screened 277 snap bean cultivars for their reaction to sulfentrazone and found that 10 snap bean cultivars (including Navarro and Romano 71) exhibited high levels of tolerance to sulfentrazone. Tolerance was highly associated with multiple genomic regions and resembled non-target site resistance mechanisms. Saballos et al. (2022) found that cultivars ‘Oregon 5402’ and ‘DMC 0488’ were also sensitive to sulfentrazone. The previous research and results from the present study suggest that the Navarro cultivar could be an effective source of alleles for breeding sulfentrazone-tolerant snap bean cultivars. Additionally, Taziar et al. (2017) evaluated the effectiveness of sulfentrazone at two rates (140 and 210 g ai ha^{-1}) for its ability to control two *Amaranthus* species among plants of one dry bean cultivar. Sulfentrazone caused 5% to 10% injury when applied alone within 2 WAA, and injury increased when the herbicide was co-applied with *S*-metolachlor, dimethenamid-P, or pyroxasulfone.

All cultivars were sensitive to metribuzin (Figures 1D, 2D, and 3D) and saflufenacil (Figures 1E, 2E, and 3E). Application of both of these preemergence herbicides resulted in reduced plant density, plant biomass, and canopy biomass at the lowest applied rate (0.5× rate for soybean). Diesel et al. (2014) reported that saflufenacil applied at 29 g ai ha^{-1} caused severe reduction in morphological development and grain yield of dry bean under field conditions. Soltani et al. (2010) demonstrated unacceptable crop injury and 92% to 99% reduction in shoot dry weight of seven leguminous crops, including snap bean, caused by saflufenacil when applied at 100 g ai ha^{-1} (equivalent to 2× in this study) and 200 g ai ha^{-1} (equivalent to 4× in this study). Unacceptable crop injury to snap bean at the 2× rate was reported.

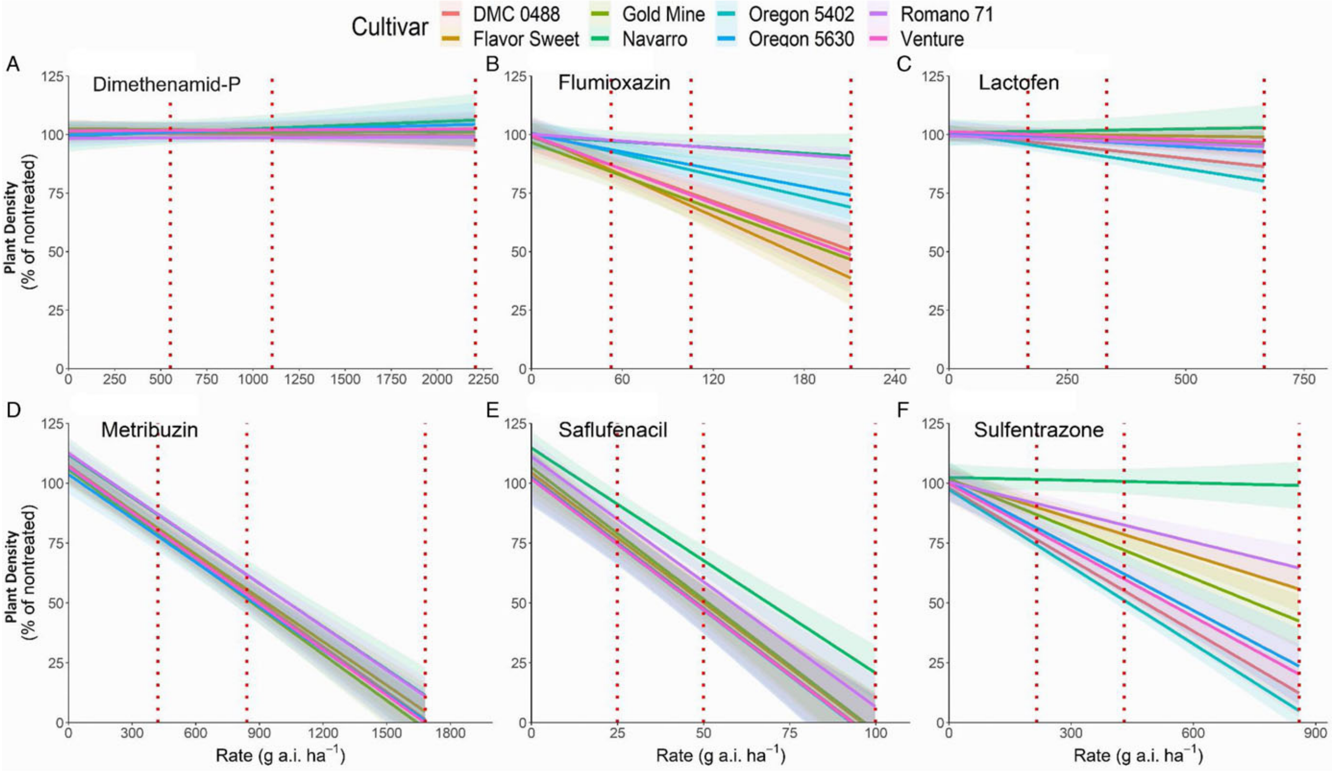

Figure 1. Effect of 0.5×, 1×, and 2× rates of A) dimethenamid-P, B) flumioxazin, C) lactofen, D) metribuzin, E) saflufenacil, and F) sulfentrazone on snap bean plant density. Vertical dotted lines represent 0.5×, 1×, and 2× use rates for soybean.

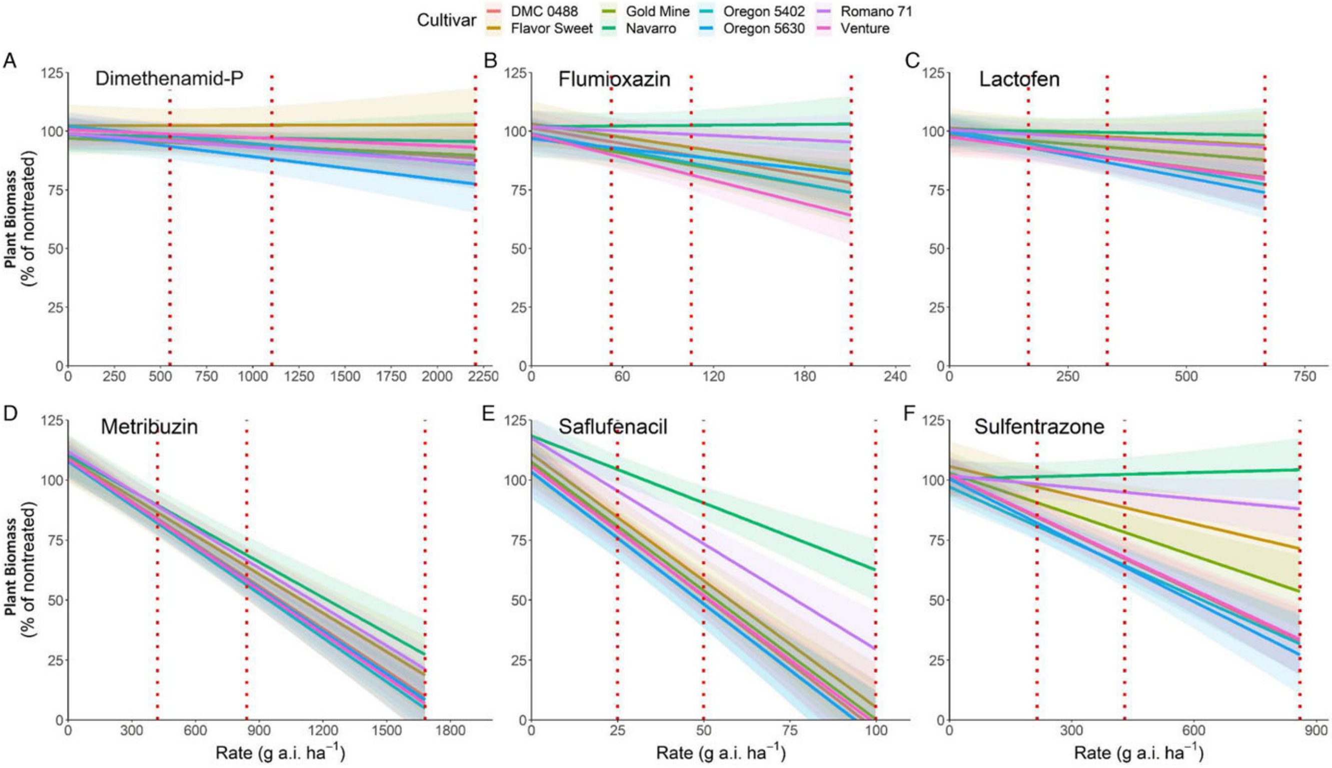

Figure 2. Effect of 0.5×, 1×, and 2× rates of A) dimethenamid-P, B) flumioxazin, C) lactofen, D) metribuzin, E) saflufenacil, and F) sulfentrazone on snap bean plant biomass. Vertical dotted lines represent 0.5×, 1×, and 2× use rates for soybean.

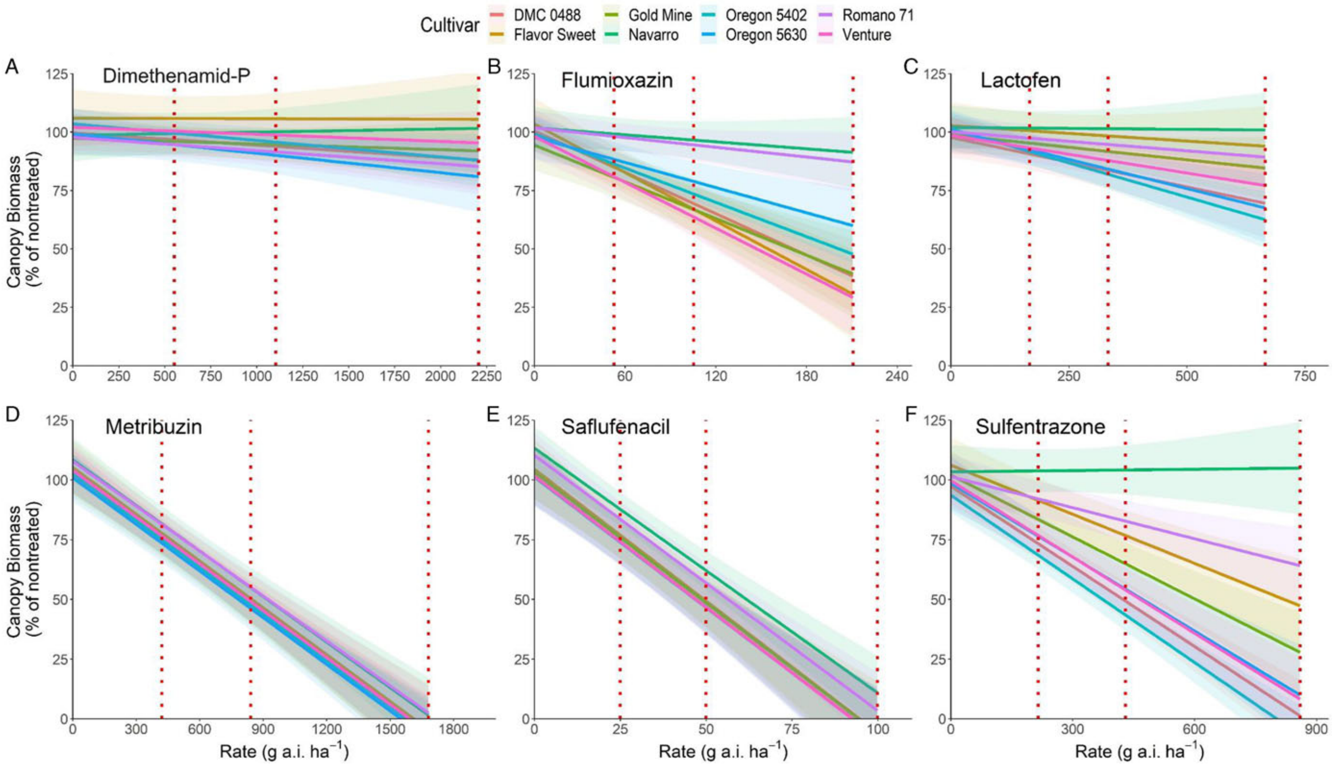

Figure 3. Effect of 0.5×, 1×, and 2× rates of A) dimethenamid-P, B) flumioxazin, C) lactofen, D) metribuzin, E) saflufenacil, and F) sulfentrazone on snap bean canopy biomass. Vertical dotted lines represent 0.5×, 1×, and 2× use rates for soybean.

In the present study, the size (i.e., 100-seed mass) of Navarro and Romano 71 seeds was relatively larger than seeds of other snap bean cultivars (Table 2), which might have contributed to the bean's tolerance to flumioxazin and sulfentrazone. Soltani et al. (2005) found that dry bean cultivars from four different market classes with large seed sizes were more tolerant to preemergence-applied flumioxazin (140 g ai ha^{-1}) than small-seeded cultivars. Viecelli et al. (2021) tested the tolerance of 36 dry bean cultivars from Brazil to sulfentrazone (400 g ai ha^{-1}) and found a positive association between seed size and crop tolerance assessed at 21 DAT. In both studies, large-seeded dry bean cultivars showed greater tolerance than small-seeded cultivars, confirming the involvement of morphological traits, particularly seed size, in the level of tolerance presented by the cultivars.

In addition to physiological and morphological traits of crops for developing tolerance, the activity of soil-applied herbicides can be influenced by soil characteristics. For example, the activity of soil-active herbicides is largely dependent on soil moisture (Stewart et al. 2012), soil pH (Grey et al. 1997; Liu et al. 2018), and organic matter content (Carneiro et al. 2020; Dos Santos et al. 2019). The adsorption and mobility of soil-applied herbicides depends on interrelated functionality of soil pH and organic matter content. Active ingredients that are less mobile in soils can potentially have lower uptake, thus impairing the herbicidal activity.

Practical Implications

Overall, these results do not support using flumioxazin, metribuzin, saflufenacil, or sulfentrazone to control *Amaranthus* species on snap bean because the margin of crop safety is insufficient. However, dimethenamid-P and lactofen may be useful for controlling weeds in snap bean crops. Furthermore, Navarro, the snap bean cultivar most tolerant to the preemergence herbicides tested in this study and in a screen by Saballos et al. (2022), may be of interest to plant breeders for sourcing genetic material to improve preemergence herbicide tolerance by snap bean. As the development of new herbicides continues to stagnate, registering current herbicides with high levels of crop safety will be valuable near-term additions to weed management systems in snap bean crops.

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Competing Interests. The authors declare they have no competing interests.

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