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Relating soil herbicide residue levels to sugar beet stand and growth reduction

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Abstract

One common recommendation given to farmers who suspect herbicide carryover to sugar beet (*Beta vulgaris* L.) is to conduct laboratory tests to assess herbicide residue levels in the soil. While this is often a good practice, there are currently no guidelines on how these laboratory test results relate to sugar beet damage or yield loss. Greenhouse studies were conducted in 2022 and 2023 to assess the relationship between soil residue levels of six herbicides (flumioxazin, imazamox, mesotrione, metribuzin, rimsulfuron, and terbacil) and sugar beet stand and growth reduction. At levels below the limit of detection in the laboratory, rimsulfuron reduced sugar beet stand density by more than 50% and biomass by 25%. Sugar beet stand density and biomass were reduced by about 40% and 25%, respectively, at metribuzin residue levels below the limit of detection. Similarly, flumioxazin reduced stand density and biomass by 50% at residue levels below the limit of detection. Stand density and biomass reduction due to mesotrione exceeded 50% even at residue levels below the limit of detection. Imazamox and terbacil caused minimal sugar beet stand and biomass reduction at residue levels below the limit of detection. These results demonstrate that laboratory analysis of herbicide residue levels in the soil must be accompanied by a bioassay to determine the potential crop damage from herbicide carryover.

Plain Language Summary

One common recommendation given to farmers who suspect herbicide carryover to sugar beet is to conduct laboratory tests to assess herbicide residue levels in the soil. While this is often a good practice, there are currently no guidelines on how these laboratory test results relate to sugar beet damage or yield loss. This research project assessed the relationship between the soil residue levels of herbicides commonly used for weed control in crops commonly grown in rotation with sugar beets and potential

Abbreviations: ALS, acetolactate synthase; CEC, cation exchange capacity; HPPD, 4-hydroxyphenylpyruvate dioxygenase; LOD, limit of detection; OC, organic carbon; PPO, protoporphyrinogen oxidase; PSII, photosystems II inhibitors; VFS, vegetative filter strips.

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sugar beet stand or growth reduction. We observed that the majority of the herbicides evaluated may cause substantial sugar beet stand density and growth reduction even at concentrations too low to be detected through laboratory tests. Thus, laboratory analysis of herbicide residue levels in the soil must be accompanied by planting crop seeds in soils with herbicide residues to determine the potential crop damage from herbicide carryover.

1 | INTRODUCTION

Chemical weed control is a common practice in agriculture. Farmers began using herbicides due to their affordability, quick action in the field, and ease of application (Paul et al., 2024). Even when properly applied according to label instructions, herbicides applied in previous seasons can still have an impact on the emergence and growth of herbicide-sensitive crops such as sugar beet (*Beta vulgaris* L.) (Frank, 1966; Riddle et al., 2013; Wittenbach et al., 1994). This is because the risk of herbicide carryover from the previous season is influenced by a myriad of factors (e.g., physical and chemical behavior of herbicide in the soil, soil type, organic matter (OM) content, and pH, etc.), most of which farmers have little to no control over. For example, dinitroanilines dissolve poorly in water and have a high organic carbon (OC)–water partition coefficient and octanol–water partition coefficient. This indicates these herbicides are more likely to build up in microorganisms over time (Vighi et al., 2017). Herbicides belonging to groups like triazines, isoxazolidinones, and imidazolinones persist in the soil and can harm the subsequent crop (Janaki et al., 2015). Sugar beet grown in soils with high herbicide residues would often show stunted canopy growth and poor root growth, with a concomitant decrease in stand density, biomass, and root yield. Fomesafen, a protoporphyrinogen oxidase (PPO) herbicide, reduced chlorophyll content in sugar beet plants, likely decreasing photosynthesis. With an increase in fomesafen concentration to 225 g ai ha^{-1}, sugar beet plant height, root length, and biomass were significantly reduced (Li et al., 2022). According to Renner and Powell (1991), imazaquin, an imidazolinone applied 1 year before planting, caused about 40% injury in sugar beet. When sugar beets were grown after maize (*Zea mays* L.), the residue of nicosulfuron applied at a rate of 0.3 μg kg^{-1} reduced the growth of sugar beet. Similarly, the height, leaf area, and dry weight of shoot and root continued to decrease as nicosulfuron increased until a lethal dose was reached at 36 μg kg^{-1} (Zhao et al., 2024). Stand establishment and yield of sugar beet were reduced when sugar beets were planted 9 months after the application of imazamox and imazapyr (Süzer & Büyük, 2010).

Soil properties also play a crucial role in determining herbicide carryover to subsequent crops. The persistence and fate of herbicides in soil are influenced by various physicochemical characteristics, including clay content, cation exchange capacity (CEC), pH, and OC content (Guimarães et al., 2018). These properties affect herbicide adsorption, degradation, and mobility, ultimately impacting their potential to carry over and affect rotational crops. Adsorption is a major factor controlling herbicide persistence, activity, and mobility in soils (Wauchope & Koskinen, 1983). Soil OM forms a solid solution with herbicides, and the Freundlich equation, which relates the amount of herbicide adsorbed to the equilibrium concentration in a solution, is commonly used to describe this adsorption process (Singh, 2009). The loss in free energy of different herbicides upon adsorption to wetted soil surfaces is similar to and slightly less than the loss upon adsorption to solid herbicides themselves. This adsorption behavior influences the availability of herbicides for degradation and potential carryover. Soil texture, particularly clay content, can significantly impact herbicide carryover. Clay particles have a high surface area that herbicides can be adsorbed to, potentially increasing their persistence in the soil. Similarly, soils with higher CEC tend to retain herbicides more strongly, potentially leading to increased carryover risk (Guimarães et al., 2018). Soil pH also plays a role in herbicide behavior, with some herbicides being more persistent in alkaline soils. For instance, sulfonylurea herbicides have been found to inhibit soil N-cycling in alkaline or low OM soils, which could affect subsequent crops (Rose et al., 2016). The OC content is another critical factor influencing herbicide carryover. Soils with higher OC content generally have greater herbicide adsorption capacity, which can lead to increased persistence. For example, the degradation half-life values for hexazinone were found to correlate with soil OC content (Guimarães et al., 2018). However, higher OC content can also promote microbial activity, potentially enhancing herbicide degradation and reducing carryover risk. The interplay between soil properties and herbicide characteristics can result in varying levels of carryover risk. A field study on imidazolinone herbicides found that soil activity (carryover) was detected over 10 months after application, with the imazapyr/imazapic mixture being the most persistent (Alister & Kogan, 2004). The sensitivity of rotational crops to these residues varied, with sugar beet being the most sensitive and maize being the least affected.

The complex nature of herbicide persistence and carryover to subsequent crops suggests that even if farmers do everything right, there is still a possibility that herbicides could carry over from previous seasons. One common recommendation given to farmers who suspect herbicide carryover to sugar beet is to conduct laboratory tests to assess herbicide residue levels in the soil. While this is often a good practice, there are currently no guidelines on how these laboratory test results relate to sugar beet damage or yield loss. This study evaluated six herbicides (flumioxazin, imazamox, mesotrione, metribuzin, rimsulfuron, and terbacil) commonly used for weed control in sugar beet rotations in our region. Flumioxazin is an *N*-phenylphthalimide PPO-inhibitor herbicide (Niekamp et al., 1999) and it is commonly used for pre-emergence weed control in alfalfa (*Medicago sativa* L.), dry bean (*Phaseolus vulgaris* L.), maize, mint (*Mentha* spp.), and potato (*Solanum tuberosum* L.). Imazamox and rimsulfuron are both acetolactate synthase (ALS) inhibitor herbicides. Imazamox is commonly used in alfalfa and dry bean, while rimsulfuron is commonly used in potatoes. Metribuzin and terbacil are photosystem II inhibitors (PSII), with metribuzin being widely used in crops like alfalfa, maize, and potato, while terbacil is mostly used in alfalfa and mint. Mesotrione is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor herbicide commonly used for pre- and post-emergence weed control in maize. The objective of the study was to assess the relationship between soil residue levels of these six commonly used herbicides in sugar beet rotations and sugar beet stand and growth reduction.

Core Ideas

- At residue levels below the limit of detection, metribuzin reduced sugar beet density by 40% and biomass by 25%.
- At residue levels below the limit of detection, rimsulfuron reduced sugar beet density by >50% and biomass by 25%.
- Mesotrione reduced stand density and biomass by >50% at residue levels below the limit of detection.
- Imazamox and terbacil caused minimal sugar beet stand and biomass reduction below the limit of detection.
- Laboratory analysis of herbicide residue must be accompanied by a bioassay to determine potential crop damage.

2 | MATERIALS AND METHODS

Greenhouse studies were conducted at the University of Idaho Kimberly Research and Extension Center in 2022 and repeated in 2023 to assess the relationship between herbicide residue in the soil and sugar beet growth. The experiment was established as a 6 × 5 factorial completely randomized with five replications. Factor A (Herbicide): flumioxazin (Chateau EZ Valent U.S.A. LLC Agricultural Products), imazamox (Raptor herbicide, BASF Ag Products), mesotrione (Callisto, Syngenta Crop Protection, LLC), metribuzin (TriCor 4F, UPL NA Inc.), rimsulfuron (Matrix FNV, Corteva Agriscience), and terbacil (Sinbar WDG NovaSource, Tessenderlo Kerley, Inc.).

The typical use rates of these herbicides are included in Table 1. Factor B (herbicide residue level): 0x, 0.1x, 1x, 10x, and 100x. Where x is the limit of detection (LOD) (Table 1). The LOD is the lowest concentration that a laboratory can reliably distinguish from a blank sample. In this study, we utilized LOD values from South Dakota Agricultural Labs (Brookings, SD), a commercial laboratory that provides worldwide analytical services. The LOD values from South Dakota Agricultural Labs are representative of the residue detection capabilities of commercial laboratories where growers in our region send samples for herbicide residue analysis. The field soil used was a Portneuf silt loam (coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) with 22% sand, 72% silt, and 6% clay, and it had a pH of 7.8, OM of 2.3%, and a CEC of 18.8 meq/100 g soil. Silt loam is among the dominant soils in sugar beet growing areas in our region. The soil was air-dried and 3-L pots were filled with 1640 g of soil. Thus, the herbicide rates were determined based on the LOD values and the weight of soil per pot. All calculations and randomization were accomplished using ARM software (Gylling Data Management, Inc.). Ten seeds of glyphosate-resistant sugar beet (Roundup Ready) seeds (BTS 278N) were planted (~1.5-cm deep) per pot in October 2022 (first run) and June 2023 (second run). Herbicides were applied within 24 h after planting using a generation 4 research track sprayer (DeVries Manufacturing Corp.) fitted with a single 8002E

TABLE 1 Herbicide limits of detection used to calculate residue levels and the typical use rate of the herbicides used in the study.

Herbicide	Limit of detection (μg kg^{-1})	Typical use rate (g ai ha^{-1})
Flumioxazin	2	60.6
Imazamox	1	44
Mesotrione	3	105
Metribuzin	6	560
Rimsulfuron	0.3	26.3
Terbacil	3	2240

Note: Limits of detection values were obtained from South Dakota Agricultural Labs (https://sdaglabs.com/).

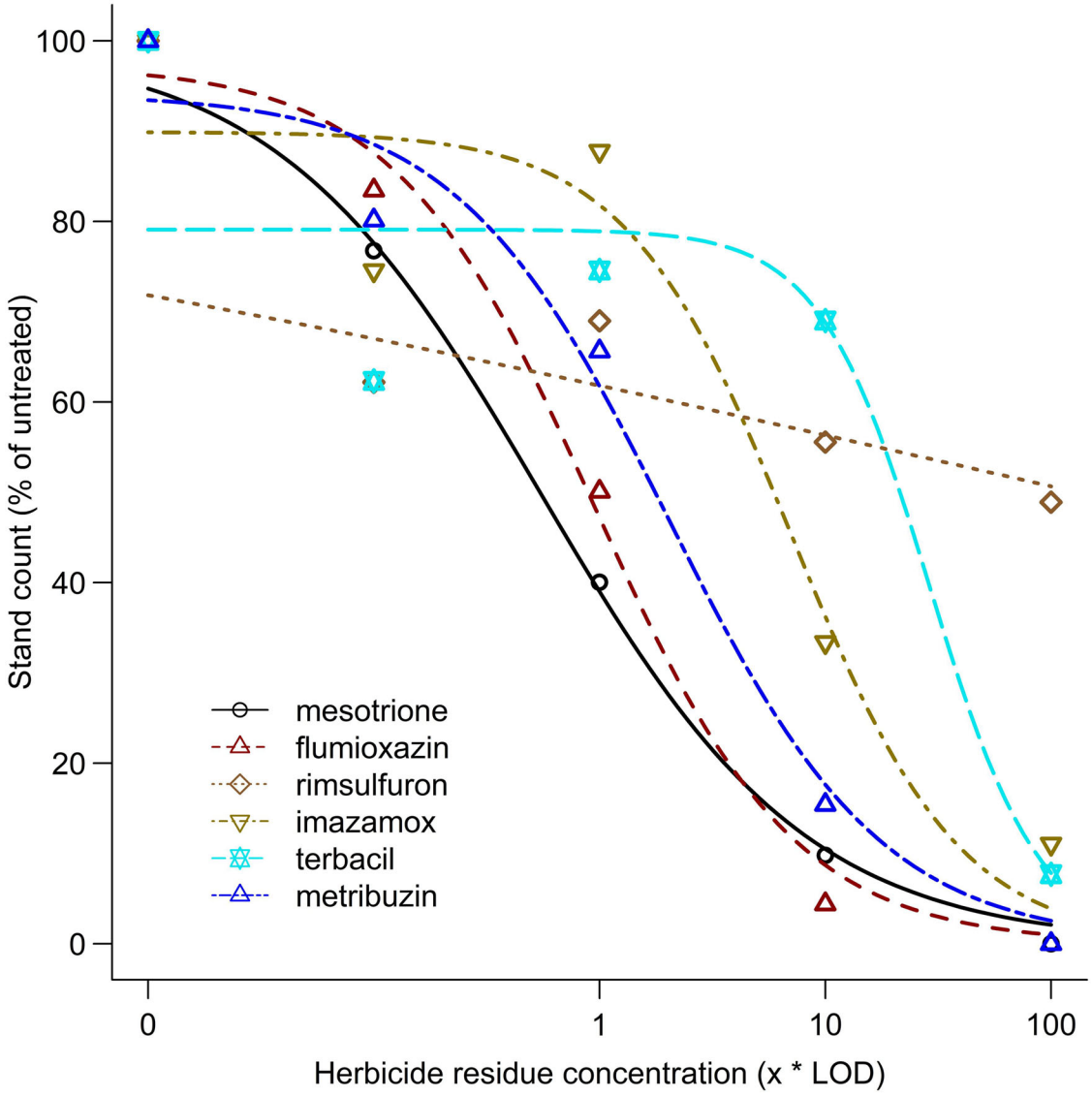


FIGURE 1 Relationship between sugar beet stand density (as a % of the untreated) and the concentrations of six herbicides in field soil. x is the limit of detection (LOD) of each herbicide as described in Table 1. LOD is the lowest concentration that a laboratory can reliably distinguish from a blank sample. An asterisk (*) was used represent multiplication. The best-fit model for flumioxazin, imazamox, mesotrione, metribuzin, and terbacil was a three-parameter log-logistic model, $y = d/(1 + (x/e)^b)$, parameters are described in Equation (1). Best-fit model for rimsulfuron was a simple linear model, $Y = 73 - 0.3X$ ($p < 0.001$).

nozzle (TeeJet, Spraying Systems Co.) calibrated to deliver 188 L ha^{-1} of carrier volume at 207 kPa. The experiment was conducted under 14/10 h day/night photoperiod with 25 ± 2°C day and 22 ± 2°C night temperatures, and sprinkler irrigated once a day till harvest (~70 days after planting).

Sugar beet were not thinned because some of the herbicides (e.g., mesotrione, metribuzin, and terbacil) were expected to kill seedlings after they emerge and were exposed to light. All emerged plants that survived were counted right before biomass harvest. Plants were harvested 70 days after planting and were separated into leaves and roots. These were oven-dried to a constant weight at 60°C for about 72 h to measure leaf and root dry weight and biomass.

2.1 | Data analysis

Nonlinear regression analysis was performed using the DRC package (v3.0-1) in the R statistical language (v 4.4.2) to quantify the effect of herbicide treatments on stand density and total biomass (R Core Team, 2024; Ritz et al., 2015). Although leaf and root biomass were weighed separately, statistical analysis showed that leaf and root biomass responses were identical; therefore, leaf and root biomass were combined into total biomass for analysis. A three-parameter log-logistic model (Seefeldt et al., 1995) (Equation 1) was used to analyze the effect of herbicide residue level on sugar

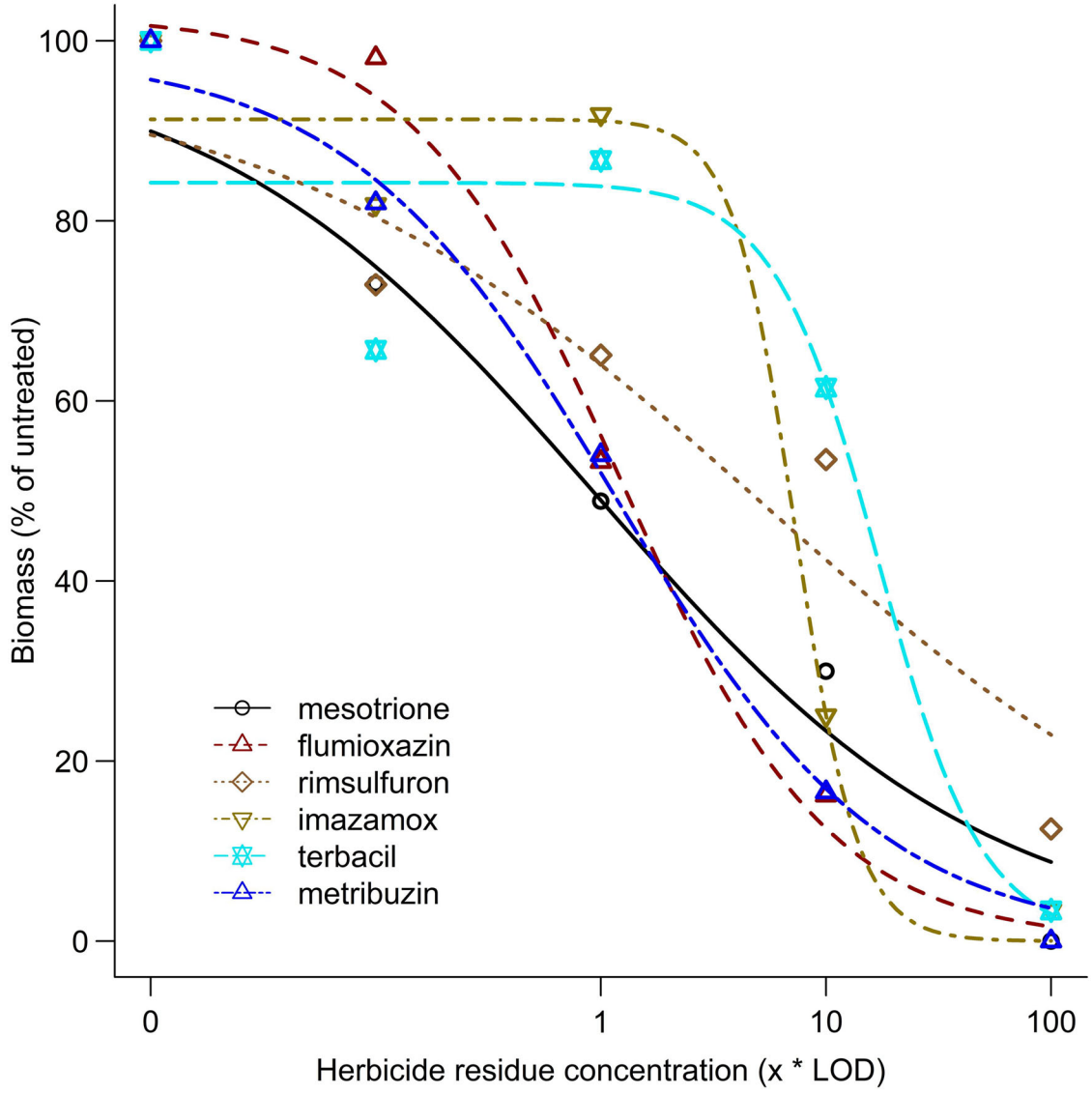


FIGURE 2 Relationship between sugar beet dry biomass (as a % of the untreated) and the concentrations of six herbicides in field soil. *X* is the limit of detection (LOD) of each herbicide as described in Table 1. LOD is the lowest concentration that a laboratory can reliably distinguish from a blank sample. An asterisk (*) was used to represent multiplication. The best-fit model for flumioxazin, imazamox, mesotrione, metribuzin, and terbacil was a three-parameter log-logistic model, $y = d/(1 + (x/e)^b)$, parameters are described in Equation (1). Best-fit model for rimsulfuron was a simple linear model, $Y = 90 - 0.6X$ ($p < 0.001$).

beet stand density and total biomass, where y = response variable (stand density [% of the untreated] or total biomass [% of the untreated]), x = herbicide residue rate/concentration, b = slope at inflection point, d = upper limit (maximum stand density or total biomass as a % of the untreated), and e = herbicide residue concentration giving 50% response (effective-dose 50% [ED50]). The model provides appropriate statistical parameter estimates of plant response and also has parameter estimates with meaningful biological interpretations.

$$y = d/\left(1 + (x/e)^b\right). \quad (1)$$

The nonlinear models were compared to linear models using Akaike information criterion to select the best-fit model. The ED function was used to calculate the level of herbicide residue needed for 5%, 10%, 25%, and 50% stand and biomass reduction.

3 | RESULTS AND DISCUSSION

At residue levels below the LOD, flumioxazin, mesotrione, metribuzin, and rimsulfuron caused substantial stand and biomass reduction (Figures 1 and 2; Tables 2 and 3). At flumioxazin residue levels below the LOD, sugar beet stand

density and biomass were reduced by nearly 50%. Metribuzin reduced stand density and biomass by at least 25% at residue levels below the LOD. Stand density and biomass reduction due to mesotrione exceeded 50% at residue levels below the LOD. Sugar beet stand density was reduced by more than 50% and biomass by more than 25% at rimsulfuron residue levels below the LOD. Imazamox and terbacil caused minimal sugar beet stand and biomass reduction at residue levels below the LOD. However, at or above the LOD, imazamox and terbacil caused substantial reductions in sugar beet stand and biomass. These results showed that most of the herbicides evaluated may cause substantial sugar beet stand and growth reduction at very low residue levels in the soil.

Although triflusulfuron methyl, an ALS herbicide, is labeled for weed control in sugar beet, the crop is very sensitive to sulfonylureas herbicides like rimsulfuron such that sugar beet is often used as an indicator species for sulfonylurea residue in soils (Wittenbach et al., 1994). It is, therefore, not surprising that although rimsulfuron has one of the lowest use rates of the herbicides tested (Table 1), just small levels of residue resulted in significant stand density and biomass reductions. Mehdizadeh and Abadan (2018) studied the impact of rimsulfuron on sugar beets and reported that the root biomass of sugar beets was more affected than shoot biomass. Biomass continually decreased as rimsulfuron was increased up to 0.11 μg kg^{-1} soil. Higher injury was recorded in the underground parts of sugar beets because herbicides are first absorbed by roots and then translocated to the leaves (Tao et al., 2020). In this study, root and shoot biomass responses to rimsulfuron were similar, contrary to the findings by Tao et al. (2020). According to Renner and Powell (1991), imazaquin (an ALS herbicide) applied 1 year before planting caused about 40% injury in sugar beets. When sugar beets were grown after maize, the residue of nicosulfuron (an ALS herbicide) applied at a rate of 0.3 μg kg^{-1} reduced the growth of sugar beets. Similarly, the height, leaf area, and dry weight of shoot and root continued to decrease as nicosulfuron increased until a lethal dose was reached at 36 μg kg^{-1} (Zhao et al., 2024). Stand establishment and yield of sugar beet were reduced when sugar beets were planted 9 months after the application of imazamox + imazapyr (Süzer & Büyük, 2010).

For the ALS inhibitors (imazamox and rimsulfuron), the common sugar beet injury symptoms observed included stunting, yellowing of young leaves, and purple leaf vein color. This is consistent with typical damage symptoms associated with these herbicides (Shaner, 2014).

In sensitive weeds and crops, PSII herbicides like metribuzin and terbacil kill emerging seedlings once they are exposed to light. Thus, in severe carryover situations, these herbicides cause substantial stand losses by killing emerging crop seedlings (Frank, 1966). This substantial reduction in sugar beet density and the concomitant reduction in biomass from low residues of metribuzin. The typical use rate of terbacil is about four times greater than metribuzin (Table 1). This might explain why metribuzin caused greater sugar beet damage at low residue levels compared to terbacil. Metribuzin and terbacil caused the burning of leaf tips and chlorosis (yellowing) of older leaves. This is consistent with injury symptoms often observed for PSII herbicides (Shaner, 2014).

Flumioxazin was among the herbicides that sugar beet was highly sensitive to (Figures 1 and 2; Table 3). High soil moisture following the preemergence application of herbicides like flumioxazin may cause increased bioavailability of the herbicide, resulting in increased herbicide uptake and greater crop damage. For example, rainfall at the time of dry bean emergence was reported to make them more susceptible to crop injury because rain causes herbicides like flumioxazin to splash from the soil surface onto the crop's hypocotyls, cotyledons, and growth point (Soltani et al., 2005). This can result in substantial crop stand and yield loss (Adjesiwor et al., 2020). A previous study also reported that with an increase in the concentration of the PPO herbicide fomesafen, sugar beet plant height, root length, and biomass were significantly reduced (Li et al., 2022). Thus, not only do PPO herbicides like flumioxazin reduce stand density, but they also reduce the growth of emerged seedlings. This explains the reduction in stand density and biomass even at low residue levels. In the flumioxazin-treated plants, we observed bronzing of leaves and stem girdling due to cell membrane destruction, which was consistent with injury symptoms of PPO herbicides (Shaner, 2014).

TABLE 2 Parameter estimates for sugar beet stand density and biomass as % of the untreated following the three-parameter log-logistic model for greenhouse experiments in 2022 and 2023, Kimberly, ID.

Herbicide	Parameter estimate[a] (± SE)		
	d	***b***	***e***
	Stand density as % of the untreated		
Flumioxazin[a]	97 (5.9)	1.0 (0.3)	0.9 (0.3)
Imazamox[a]	90 (5.8)	1.2 (0.7)	7.2 (2.2)
Mesotrione[a]	100 (7.0)	0.7 (0.2)	0.5 (0.2)
Metribuzin[a]	94 (7.4)	0.9 (0.3)	2.0 (0.9)
Rimsulfuron[b]	–	–	–
Terbacil[a]	79 (5.0)	1.8 (0.7)	29.0 (13.2)
	Biomass as % of the untreated		
Flumioxazin[a]	100 (10.0)	1.0 (0.4)	1.3 (0.7)
Imazamox[a]	91 (7.3)	4.5 (84.8)	8.0 (33.2)
Mesotrione[a]	99 (10.1)	0.5 (0.1)	0.9 (0.7)
Metribuzin[a]	99 (18.6)	0.7 (0.2)	1.2 (0.6)
Rimsulfuron[b]	–	–	–
Terbacil[a]	84 (7.9)	1.9 (2.0)	17.1 (11.9)

[a] $y = d/(1 + (x/e)^b)$, parameter estimates are described in Equation (1).
[b] Best fit was a simple linear model, $y = a - bx$. Rimsulfuron linear regression equations: stand density, $Y = 73 - 0.3X$ ($p < 0.001$); biomass, $Y = 90 - 0.6X$ ($p < 0.001$).

TABLE 3 Estimated herbicide residue levels that will reduce sugar beet stand density and biomass by 5%, 10%, 25%, and 50%.

	Biomass reduction				Stand density reduction			
Herbicide	**5%**	**10%**	**25%**	**50%**	**5%**	**10%**	**25%**	**50%**
	Herbicide residue concentration (μg kg^{-1})							
Flumioxazin[a]	0.11	0.23	0.76	2.44	0.09	0.20	0.61	1.88
Imazamox[a]	5.37	6.05	7.20	8.57	0.58	1.10	2.81	7.16
Mesotrione[a]	0.01	0.04	0.33	2.93	0.03	0.08	0.37	1.65
Metribuzin[a]	0.12	0.35	1.56	6.98	0.49	1.10	3.66	12.11
Rimsulfuron[b]	0.15	0.16	0.21	0.43	0.06	0.07	0.09	0.19
Terbacil[a]	9.90	15.06	27.89	51.65	16.72	25.41	47.03	87.02

[a]Based on a three-parameter log-logistic model, $y = d/(1 + (x/e)^b)$, parameters are described in Equation (1).
[b]Best fit was a simple linear model, $y = a - bx$.

Results from this study also showed that sugar beet was highly sensitive to mesotrione (Figures 1 and 2; Table 3), which confirmed findings from previous studies (Pintar et al., 2020; Riddle et al., 2013). In a previous study, it was reported that the level of mesotrione required to cause a 50% reduction in sugar beet biomass was 4.4 to 5.9 g ai ha^{-1} (Pintar et al., 2020). This is 18–24 times less than the typical use rate of 105 g ai ha^{-1}. In mesotrione, an HPPD inhibitor herbicide, the sugar beet leaves were bleached due to chlorophyll breakdown. This is a common injury symptom from HPPD herbicides (Shaner, 2014). In sugar beet, it took less than 22 times the labeled use rate of mesotrione to reduce the carotenoid content of the leaves by 50% (Pintar et al., 2020). Thus, the death of seedlings and reduced photosynthesis due to deleted chlorophyll might explain significant stand and biomass reduction from mesotrione.

Results from this study emphasize the need for research on the potential for herbicide residues to negatively affect sensitive crops, with implications for sustainable agricultural practices and food safety (Isha et al., 2022; Liu et al., 2024; Locke & Bryson, 1997; Wilson et al., 1995). Cultivation practices can influence herbicide persistence (Janaki et al., 2015). Soil properties such as OM, moisture, and texture play a vital role in the persistence of herbicides in the soil (Süzer & Büyük, 2010). Therefore, decomposed plant residues, cover crops, and tillage practices affect the availability of herbicides in the soil (Reddy et al., 1997). For instance, the use of ryegrass as a cover crop in conventional tillage systems helped with herbicide degradation by stimulating microbial activity in the soil (Zablotowicz et al., 2007).

One effective strategy is the careful selection of herbicides with shorter half-lives and lower persistence in soil. A field study on imidazolinone-resistant maize found that the mixture of imazapyr and imazapic was more persistent than imazapyr and imazethapyr, with soil activity detected over 10 months after application (Alister & Kogan, 2004). This highlights the importance of choosing herbicides that are less likely to carry over to subsequent growing seasons. Crop rotation and diversification have been identified as crucial practices for reducing herbicide carryover. The integration of cover crops and service crops can help in managing herbicide residues and improving soil health (Tataridas et al., 2022). The use of vegetative filter strips (VFS) has shown promise in reducing herbicide runoff and, consequently, the potential for carryover. Parameters affecting herbicide retention in VFS include the width of the strip, area ratio, species established, time after establishment, antecedent moisture content, and herbicide properties (Krutz et al., 2005). Implementing VFS can enhance herbicide sorption and degradation, thereby reducing subsequent transport to adjacent cultivated soil. Integrated weed management approaches that combine chemical and nonchemical methods can help reduce overall herbicide use and the risk of carryover (Tataridas et al., 2022).

4 | CONCLUSIONS

Herbicides such as metribuzin, rimsulfuron, flumioxazin, and mesotrione are commonly used for weed control in crops commonly grown in rotation with sugar beets, and these may cause substantial sugar beet stand density and growth reduction even at concentrations too low to be detected through laboratory test. Thus, laboratory analysis of herbicide residue levels in the soil must be accompanied by a bioassay to determine the potential crop damage from herbicide carryover. There is also the need for further research on herbicide residues impacting sensitive crops to serve as guidelines for farmers and agronomists.

AUTHOR CONTRIBUTIONS

Adam R. Kennedy: Writing—original draft; writing—review and editing. **Sushmita K. Sharma**: Writing—original draft; writing—review and editing. **Clarke G. Alder**: Conceptualization; funding acquisition; writing—review and editing. **Albert T. Adjesiwor**: Conceptualization; data curation;

formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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