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A follow-up survey to assess stakeholders' perspectives on weed management challenges and current practices in Nebraska, USA

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Abstract

Stakeholders across the state of Nebraska, USA, were surveyed in 2019–2020 to assess problem weeds and weed management practices in agronomic crops. A total of 420 complete responses were obtained across four Nebraska districts (Northeast, Panhandle, Southeast, and West Central). Accumulated across the state, 65.5% of farmed or scouted crop ground in Nebraska was under no-till production, with the major crops being corn and soybean representing 39.3% and 30.7% of agronomic crop production area, respectively. Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed were ranked the most problematic weeds. In a 2014–2015 survey, Palmer amaranth was the sixth most problematic weed. The most used preplant herbicides were 2,4-D, glyphosate, and dicamba in the 2019–2020 survey. Atrazine applied alone or in mixture with acetochlor, bicyclopyrone, clopyralid, mesotrione, or *S*-metolachlor were the most applied pre-emergence (PRE) herbicides in corn, whereas the most applied PRE herbicides in soybean were metribuzin/sulfentrazone, flumioxazin/pyroxasulfone, and chloransulam-methyl/sulfentrazone. Like the previous survey, glyphosate was the most frequent choice of survey respondents as a post-emergence (POST) herbicide in glyphosate-resistant corn and soybean, while 2,4-D was the most applied POST herbicide in grain sorghum and wheat. Most of the respondents (77%) were aware of the new multiple herbicide-resistant crops, and 86% listed physical drift and volatility of dicamba/2,4-D as a primary concern. Twenty-three percent of survey respondents identified integrated pest management as a primary research and extension priority for profitable agronomic crop production in Nebraska.

Abbreviations: ALS, acetolactate synthase; GR, glyphosate-resistant; HPPD, 4-hydroxyphenylpyruvate dioxygenase; NA, not available; NASS, National Agricultural Statistics Service; POST, post-emergence; PRE, pre-emergence; SEM, standard error of the mean; SOA, site of action; USDA, United States Department of Agriculture.

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1 | INTRODUCTION

The rapid adoption of glyphosate-resistant (GR) crops since their commercialization in 1996 has greatly impacted the pattern of herbicide use in modern agriculture (Benbrook, 2016). From 1974 to 2014, an estimated 8.6 billion kg of glyphosate has been applied worldwide, with the United States accounting for 19% or 1.6 billion kg of global usage (Benbrook, 2016). Use of glyphosate in the United States was estimated at a total of 18 million kg year^{-1} in 1996, increasing to an estimated 125 million kg year^{-1} in 2013 (USGS, 2020). In large part, the popularity of glyphosate can be attributed to the widespread application of glyphosate in GR crops due to its low application cost per unit area and broad spectrum of weed control (Woodburn, 2000). As of 2022, six weed species, including common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), horseweed (*Erigeron canadensis* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], Palmer amaranth (*Amaranthus palmeri* S. Watson), and waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer] have been confirmed resistant to glyphosate in Nebraska (Heap, 2023).

As multiple herbicide-resistant crops have come to market in recent years, the options for selecting herbicides for post-emergence (POST) weed control have increased. Since its commercialization in 2017, the area under dicamba/glyphosate-resistant soybean planted in Nebraska has increased from 20% in 2017 to 80% in 2019 (Werle et al., 2018). The adoption of conservation tillage and changes in weed management practices significantly altered weed population dynamics (Nichols et al., 2015), with a major shift toward smaller seeded broadleaf weeds such as *Amaranthus* spp. (Kruger et al., 2009). As the adoption of GR crops increased in popularity, there has been a shift toward reduced usage of tillage for weed control (Sarangi & Jhala, 2018). In 2014–2015, a statewide survey was conducted in Nebraska to report problem weeds, commonly used herbicides, other management practices, and weed management needs of stakeholders (Sarangi & Jhala, 2018). In that survey, paper copies of a questionnaire were distributed to the participants of the University of Nebraska Extension's winter meetings. A follow-up survey was conducted in 2019–2020 using an updated version of the previous 2014–2015 questionnaire. This survey was conducted to evaluate the changes in problem weeds and weed management practices being adopted by growers in agronomic crops in Nebraska.

The Nebraska Extension is consisted of 83 county offices and four extension centers serving 93 counties throughout the state. A survey was developed for participants (growers, certified crop advisors, crop consultants, certified pesticide applicators, cooperative managers, and industry representatives) attending the Nebraska Extension's meetings, Extension field days, and an online version of the survey was distributed through the cropwatch.unl.edu website. The objectives of this survey were to assess stakeholders' current perspectives and challenges on problem weeds, and agronomic and weed management practices used by growers in Nebraska. The results of this survey were compared with the 2014–2015 survey to record and account for differences. A follow-up survey is important to determine the changes in the weed species distribution, occurrence, and learn about management options adopted by growers. In addition, surveys conducted at regular intervals can help researchers and extension personnel to identify research/extension priorities and solve their problems related to weed management.

Core Ideas

- After conducting a survey in 2014–2015, a follow-up survey was conducted in 2019–2020 to assess problem weeds.
- A total of 420 responses across four Nebraska districts (Northeast, Panhandle, Southeast, and West Central) were recorded.
- Palmer amaranth was ranked the most problematic weed across the state in the 2019–2020 survey.
- Survey results showed that 77% of respondents were aware of new multiple herbicide-resistant crops.

2 | MATERIALS AND METHODS

A survey was distributed online (www.cropwatch.unl.edu) as well as in person at several locations during summer and winter extension meetings organized by the Nebraska Extension in 2019–2020. Paper questionnaires were distributed to in-person participants, while online participants received a web-based format; questions were mostly short answer-type or open-ended, but some closed questions were also included (see the Appendix). Prior to release, the questionnaire was reviewed by 10 people, including weed scientists and agronomy undergraduate and graduate students, to assess its acceptability and readability. The questionnaire was divided into four sections (see the Appendix). Survey responses were separated by counties representing four major Extension districts defined by the Nebraska Extension based on their agro-climatic characteristics, soil texture, and cropping systems (Figure 1). Respondents were asked to state occupation, county, and state of residence. Respondents who were not directly involved in farm management and/or operations or agribusiness decision-making were disqualified along with the individuals who did not reside in Nebraska.

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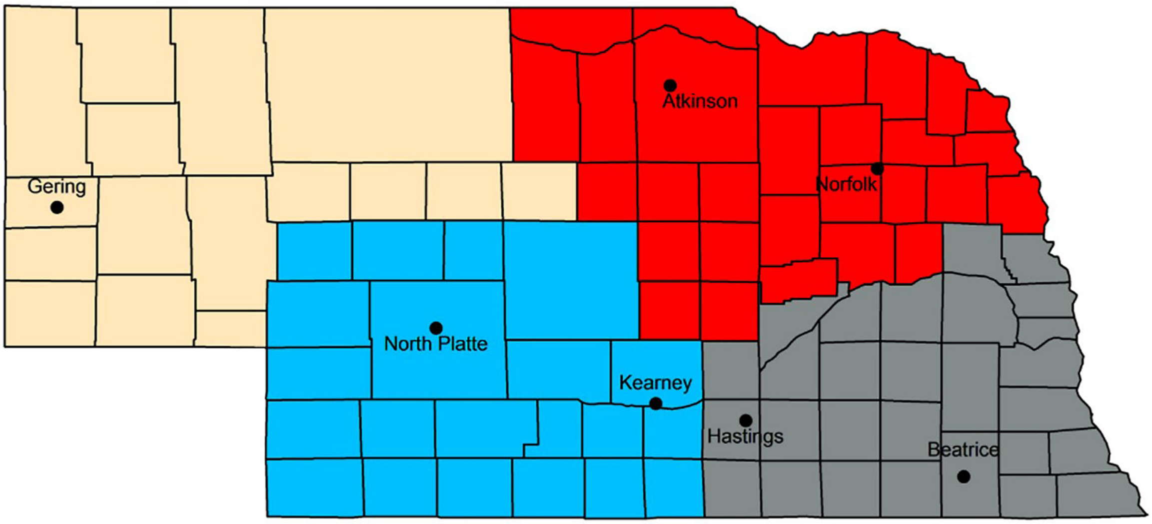

FIGURE 1 County map of Nebraska divided into four districts (Northeast, Panhandle, Southeast, and West Central) based on their agro-climatic characteristics, soil texture, and cropping systems.

TABLE 1 Number of survey respondents categorized based on occupation in a 2019 survey of stakeholders in Nebraska to assess problem weeds and their management practices in agronomic crops.

Occupation	Districts				Nebraska
	Northeast	Panhandle	Southeast	West Central	
	Number of respondents				
Growers	67	20	131	48	266
Crop Consultants[a]	28	8	54	20	110
Others[b]	12	4	20	8	44
Total Respondents	107	32	205	76	420

[a]Survey respondents with the primary occupations of certified crop advisors and agronomist were considered as "crop consultants."

[b]Survey respondents not categorized as growers or crop consultants were considered "others," which included pesticide applicators, farm workers, farm managers, and industry sales representatives.

A total of 420 valid responses were recorded and processed from the 2019–2020 statewide survey. Respondents were categorized into three groups based on their occupation: growers, crop consultants, and others. Growers were respondents who owned farmlands or directly participated in farm operations and/or decision-making on farms. Respondents who reported an occupation of agronomist, certified crop advisor, or crop consultant were categorized as crop consultants. Those who did not fit into the grower or crop consultant categories, such as pesticide applicators, cooperative managers, or industry representatives, were categorized as others. Out of 420 respondents, 48%, 32%, and 20% were categorized as growers, crop consultants, and others, respectively (Table 1).

A relative problematic/importance points system as described by Sarangi and Jhala (2018) was used to rank the most problem weeds and the most used herbicides in Nebraska. In this method, five, four, three, two, and one problematic points were assigned to rank #1, #2, #3, #4, and #5 problem weeds, respectively (Question 1.3 in Appendix), and the relative problematic point (RP) was calculated for each weed species using the following equation (Sarangi & Jhala, 2018):

$$\mathrm{RP} = \sum_{r=1}^{5} \frac{FX}{n}, \tag{1}$$

where F is the number of respondents selecting a rank (r) for a weed species, X is the problematic points associated with that rank, and n is the total number of responses for that rank, including all the weed species. Similarly, the most used preplant burndown, pre-emergence (PRE), and POST herbicides (Questions 2.1–2.3 in Appendix) were ranked based on their level of importance. The relative importance point for a herbicide was calculated using Equation (1), with an r value ranging from 1 to 3. Data were imported to R (R Core Team, 2020), and the results were interpreted based on the frequency distribution and their mean and median values.

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TABLE 2 Information on average farm size, areas in no-till production, and primary crops in a 2019 survey of stakeholders in Nebraska to assess problem weeds and their management practices in agronomic crops.

Category of area	Districts[a] Northeast[b]	Panhandle	Southeast[b]	West Central[b]	Nebraska
Farming areas (ha) by growers	760 (132)	780 (352)	850 (96)	920 (201)	798 (83)
Scouted areas (ha) reported by crop consultants	4385 (1244)	3267 (1453)	6154 (1395)	3421 (1102)	4828 (762)
Area under no-till production (% of total area farmed or scouted)	67	49	75	56	65
Area under primary crops (% of total area farmed or scouted)					
Corn	47	26	48	26	39
Soybean	41	18	39	33	31
Grain sorghum	1	9	7	14	3
Wheat	6	16	4	15	5
Alfalfa	5	8	6	5	4
Dry edible bean	NA	5	NA	NA	NA
Sugar beet[b]	NA	12	NA	NA	NA
Others	1	24	1	4	4

Note: Values in parentheses represent the standard error of the mean (SEM).
Abbreviation: NA, not available (respondents did not report).
[a]Responses of growers and the crop consultants were considered for this question.
[b]Sugarbeet was reported only from the Panhandle district of Nebraska; therefore, average state results were not calculated.

3 | RESULTS AND DISCUSSION

3.1 | Crop production

The average farmed areas reported by growers for 2019–2020 survey were 760, 780, 850, and 920 ha per capita in the Northeast, Panhandle, Southeast, and West Central districts, respectively, with a state average of 798 ha (Table 2). In contrast, averaged farmed areas in the 2014–2015 survey were 710, 829, 814, and 961 ha in the Northeast, Panhandle, Southeast, and West Central districts, respectively, with a state average of 801 ha (Sarangi & Jhala, 2018). The Census of Agriculture conducted by the United States Department of Agriculture (USDA) in 2012 and 2017 found that the average size of a Nebraska farm was 907 and 971 acres, respectively; however, in contrast to our survey, where respondents were mostly row crop producers, the USDA census data included farm areas under row crops and other commodity production systems such as livestock operations (USDA-NASS, 2014, 2019). Crop consultants participating in the 2019–2020 survey scouted average areas ranging between 3267 and 6154 ha in different districts, with a state average of 4828 ha (Table 2). Similarly, crop consultants participating in the 2014–2015 survey scouted average areas ranging between 3151 and 5869 ha, with a state average of 4662 ha (Sarangi & Jhala, 2018). The maximum area under no-till production in the 2019–2022 survey was reported from the Southeast district (74.6%), followed by the Northeast (67.2%), West Central (56.1%), and Panhandle (48.8%) districts, with the state average for no-till production area being 65.5%. According to the 2012 and 2017 Census of Agriculture, each Nebraska farm consisted of an average of 57% and 61% no-till production, respectively (USDA-NASS, 2014, 2019).

3.2 | Agronomic crop areas in Nebraska

The results of the 2019–2020 survey showed that corn and soybean were the major crops in Nebraska, with 39.3% and 30.7% of the total farmed or scouted area reported, respectively (Table 2) compared with 82.3% of corn and soybean combined with total farmed or scouted area in the 2014–2015 survey (Sarangi & Jhala, 2018). The data from USDA-NASS in the 2014 growing season reported that up to 75% of Nebraska cropland was under corn and soybean production (USDA-NASS, 2015) compared with 81% in 2022 (USDA-NASS, 2022). A 2019-2022 survey results indicated that the highest corn-growing regions were the Southeast district (48.2% of total farmed or scouted area), followed by the Northeast (46.5%), West Central (26%), and Panhandle (26%) districts. The maximum soybean-growing regions were ranked as the Northeast (41%), Southeast (39.3%), West Central (33%), and Panhandle (18%) districts. It must be noted that no soybean production area was reported from the Panhandle district in a 2014–2015 survey (Sarangi & Jhala, 2018). This might be because historically soybean is not a major crop in Nebraska Panhandle; however, soybean area has increased in last few years in Nebraska Panhandle. The Panhandle district was the only district to yield responses for dry edible bean (*Phaseolus vulgaris* L.) and sugarbeet (*Beta vulgaris* L.) production, which consisted of 5% and 12%, respectively (Table 2). This was expected because dry edible bean and

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TABLE 3 Respondents' ranking of most difficult-to-control weeds in a 2019–2020 survey of stakeholders in Nebraska.

Rank	Districts: Northeast	Panhandle	Southeast	West Central	Nebraska
	Name of Name of problem weed				
1	Palmer amaranth (3.9)	Kochia (4.4)	Palmer amaranth (4.0)	Palmer amaranth (4.2)	Palmer amaranth (3.6)
2	Common waterhemp (3.6)	Palmer amaranth (3.6)	Horseweed (3.8)	Kochia (2.9)	Horseweed (3.2)
3	Horseweed (3.0)	Field bindweed (1.5)	Common waterhemp (3.7)	Common waterhemp (2.7)	Common waterhemp (3.1)
4	Kochia (1.9)	Horseweed (0.7)	Velvetleaf (1.6)	Horseweed (2.2)	Kochia (1.8)
5	Giant ragweed (1.1)	Velvetleaf (0.6)	Kochia (0.8)	Foxtails (0.9)	Giant ragweed (0.8)

Note: Values in parentheses represent problematic points for a weed, calculated using the equation:
$RP = \sum_{r=1}^{5} \frac{FX}{n}$,
where F is the number of respondents choosing a particular rank (r) for a weed species, X is the number of problem points (5 for rank #1, 4 for rank #2, 3 for rank #3, 2 for rank #4, 1 for rank #5) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum number of relative problematic points for a weed species is 5.0.

sugarbeet are typically grown in Nebraska Panhandle. Results indicated that the areas in Nebraska under grain sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum* L.), and alfalfa (*Meticago satvia*) production were 2.7%, 4.9%, and 4.1%, respectively (Table 2). Other crops, including hay, cereal rye (*Secale cereal* L.), and oat (*Avena satvia* L.), together accounted for 3.6% of the total agronomic crop production in Nebraska.

3.3 | Problem weeds

The top five most difficult to control weeds across Nebraska in a 2019–2020 survey were Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed (Table 3). In contrast, waterhemp, horseweed, kochia, velvetleaf, and common lambsquarters were the top five most difficult to control weeds in a 2014–2015 survey (Sarangi & Jhala, 2018). In fact, Palmer amaranth was ranked the sixth most difficult to control weed in a 2014–2015 survey compared with the first in a 2019–2020 survey. A 2016 and 2020 survey by the Weed Science Society of America ranked Palmer amaranth as the most troublesome weed in the United States (Van Wychen, 2016, 2021). Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed have a confirmed glyphosate-resistant population in Nebraska (Chahal et al., 2017; Ganie et al., 2016; Rana & Jhala, 2016; Sandell et al., 2011; Sarangi, Sandell, Knezevic, et al., 2015; Sarangi, Sandell, Kruger, et al., 2015; Sarangi & Jhala, 2017), which has likely led to these being the most challenging weeds to manage. In a multistate grower survey conducted in 2005–2006, Kruger et al. (2009) reported that waterhemp, velvetleaf, and foxtails were the three most problematic weeds in GR corn and soybean rotation in Nebraska; however, due to the evolution of resistance to glyphosate and multiple herbicides in recent years, horseweed, kochia, and waterhemp now top the list as per a previous survey (Sarangi & Jhala, 2018). In the Southeast district, Palmer amaranth, horseweed, and waterhemp were identified as extremely concerning to manage, whereas respondents from the Panhandle district listed kochia and Palmer amaranth as the most problematic weeds (Table 3). In parity with the Southeast district, Palmer amaranth was listed as the most problematic weed in both the Northeast and West Central districts. Palmer amaranth resistant to atrazine and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides (Jhala et al., 2014) as well as Palmer amaranth biotype resistant to acetolactate synthase (ALS)-inhibiting herbicides, atrazine, and glyphosate has been reported in Nebraska (Chahal et al., 2017). Management of multiple herbicide-resistant Palmer amaranth is a challenge for Nebraska crop producers, and it is likely that Palmer amaranth will remain the most difficult to control weed in future surveys.

3.4 | Glyphosate-resistant weeds

Most stakeholders suspected the presence of glyphosate-resistant weeds in their agronomic crop fields in Nebraska. A small number of responses ($n = 25$) were recorded from the Panhandle district, so results were not reported (Table 4). In the Northeast district, 71%, 65%, 25%, and 12% of respondents suspected the presence of GR waterhemp, horseweed, Palmer amaranth, and giant ragweed, respectively (Table 4). In a 2014–2015 survey, 55% and 52% of respondents noted the presence of GR waterhemp and horseweed in the Northeast district and 14% and 10% reported the presence of GR giant ragweed and kochia, respectively (Sarangi & Jhala, 2018). Reports of suspected glyphosate resistance correlate

TABLE 4 Weeds listed by respondents for suspected glyphosate-resistance in a 2019–2020 survey of stakeholders in Nebraska to assess problem weeds and their management practices in agronomic crops.

	Districts		
Responses	**Northeast**	**Southeast**	**West Central**
Suspected glyphosate-resistant	Common waterhemp (71)	Palmer amaranth (61)	Palmer amaranth (63)
	Horseweed (65)	Horseweed (49)	Kochia (48)
	Palmer amaranth (25)	Common waterhemp (44)	Horseweed (37)
	Giant ragweed (12)	Giant ragweed (4)	Common waterhemp (24)

Note: Responses of growers and crop consultants were considered for this question. Values in parentheses represent the percentage of respondents who reported a certain weed species. Sufficient responses were not recorded from the Panhandle district; therefore, data from the Panhandle district were not included in this table.

with some of the most problematic weeds in this region (Table 3). About 39% of respondents reported the presence of a suspected waterhemp biotype with resistance to HPPD, and ALS-inhibitor in Palmer amaranth, waterhemp, and horseweed in the Northeast, Southeast, and West Central districts (data not shown). Prior field sampling of waterhemp biotypes from the Northeast district (Platte County) has confirmed resistance to HPPD-inhibiting herbicides (Oliveira, 2017). Most of the survey respondents in the Southeast and West Central districts listed glyphosate-resistant weeds as their primary herbicide resistance concern. In the Southeast district, 61%, 49%, 44%, and 4% of respondents reported the presence of suspected GR Palmer amaranth, horseweed, waterhemp, and giant ragweed, respectively (Table 4). A Palmer amaranth biotype from Southeast Nebraska (Thayer County) was confirmed to be 40-fold resistant to glyphosate, as well as resistant to ALS-inhibiting herbicides and atrazine (Chahal et al., 2017). While the 2014–2015 survey reported Palmer amaranth as the sixth most troublesome weed in Nebraska (Sarangi & Jhala, 2018), Palmer amaranth has become the most troublesome weed in Nebraska (Table 4). In the West Central district, 63%, 48%, 37%, and 24% of respondents suspected the presence of GR Palmer amaranth, kochia, horseweed, and waterhemp, respectively (Table 4).

3.5 | Herbicide usage

3.5.1 | Preplant herbicides

Effective weed management has been recommended for the control of standing vegetation before planting in no-till crop production systems (Stougaard et al., 1984; VanGessel et al., 2001). Participant responses across occupational classes (growers, crop consultants, and others) were compiled to rank the most used preplant herbicides in Nebraska, with the results showing that 2,4-D, glyphosate, and dicamba were the top three preplant burndown herbicides in common use in Nebraska (Table 5). In a survey conducted in 2014–2015, the top three preplant burndown herbicides were glyphosate, 2,4-D, and saflufenacil (Sharpen) (Sarangi & Jhala, 2018). Dicamba use has significantly increased in preplant burndown as well as in post-emergence applications after the commercial cultivation of dicamba-resistant soybean since the 2017 growing season (Werle et al., 2018). Several multistate surveys that included Nebraska also reported that glyphosate and 2,4-D were the most popular choices among growers for preplant herbicides (Givens, Shaw, Johnson, et al., 2009; Givens, Shaw, Kruger, et al., 2009; Prince et al., 2012). Additionally, Prince et al. (2012) reported that synthetic auxins (e.g., 2,4-D) and PPO-inhibiting herbicides were mostly used to control GR weeds.

3.5.2 | Pre-emergence herbicides

Sufficient responses for PRE herbicide usage were not obtained from the Panhandle district; therefore, survey results indicating PRE herbicide usage were not included for Panhandle district (Table 6). In Nebraska, the three most used PRE herbicides in corn were atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron), acetochlor/clopyralid/mesotrione (Resicore), and isoxaflutole/thiencarbazone-methyl (Corvus) (Table 6). In contrast, a survey conducted in 2014–2015 reported atrazine/mesotrione/*S*-metolachlor (Lexar EZ/Lumax EZ), isoxaflutole/thiencarbazone-methyl (Corvus), and acetochlor/atrazine (Degree Xtra) as the three most-used PRE herbicide in corn (Sarangi & Jhala, 2018). Other major corn herbicides were atrazine plus *S*-metolachlor (Dual II Magnum) and atrazine (data not shown). Results of the top five most used PRE herbicides in corn clearly show the dominance of atrazine-based herbicides and premixes for early season weed control. Results from a 2016 multistate survey of corn-producing states, including Nebraska, reported atrazine as the most used corn herbicide, with atrazine being applied in more than half (60%) of corn production fields (USDA-NASS, 2018).

The most used PRE herbicides in soybean were metribuzin/sulfentrazone (Authority MTZ), flumioxazin/pyroxasulfone (Fierce), and sulfentrazone/chloransulam-methyl (Authority First) (Table 6). In a survey conducted in 2014–2015, it was reported that the most used PRE herbicides in soybean were cloransulam-methyl/sulfentrazone,

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TABLE 5 Respondents' ranking of the most used preplant herbicides in a 2019–2020 survey of stakeholders in Nebraska to assess problem weeds and their management practices in agronomic crops.

Rank	Districts Northeast	Panhandle	Southeast	West Central	Nebraska
	Herbicides				
1	2,4-D (2.7)	Glyphosate (1.9)	2,4-D (2.5)	2,4-D (2.2)	2,4-D (2.7)
2	Dicamba (1.3)	Saflufenacil (1.1)	Glyphosate (1.9)	Dicamba (1.3)	Glyphosate (1.4)
3	Glyphosate (1.3)	2,4-D (0.8)	Dicamba (1.0)	Glyphosate (1.0)	Dicamba (1.3)

Note: Values in parentheses represent the relative importance points, calculated using the equation:
$RP = \sum_{r=1}^{3} \frac{FX}{n}$,
where F is the number of respondents choosing a particular rank (r) for a herbicide, X is the number of problem points (3 for rank #1, 2 for rank #2, and 1 for rank #3) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum relative importance points are 3.0.

flumioxazin (Valor SX) or flumioxazin/chlorimuron-ethyl (Valor XLT), and thifensulfuron (Harmony) (Sarangi & Jhala, 2018). Results suggest that soybean growers are highly reliant on PRE herbicides containing ALS inhibitors, very long chain fatty acid-inhibitors, and PPO inhibitors, in contrast to the more diverse PRE usage in corn. In sorghum, atrazine-based herbicides dominated the top three spots with atrazine/*S*-metolachlor/mesotrione (Lexar EZ or Lumax EZ), atrazine (Aatrex), and atrazine/*S*-metolachlor (Dual II Magnum) (Table 6). Similar commonly used PRE herbicides were reported in a 2014–2015 survey in sorghum (Sarangi & Jhala, 2018).

3.5.3 | Post-emergence herbicides

Most of the growers (73%) reported applying a POST herbicide(s) for weed control in row crops (data not shown), with glyphosate being the most used POST herbicide for weed control in GR corn and soybean (Table 6). In a 2014–2015 survey, it was reported that 80% of growers applied POST herbicide for weed control in row crops (Sarangi & Jhala, 2018). A multistate survey noted that more than 95% of the GR crop growers in 22 corn-, soybean-, and cotton-growing states, including Nebraska, applied glyphosate as their primary POST herbicide (Prince et al., 2012). In corn, the most used POST herbicides after glyphosate were dicamba/diflufenzopyr (Status) and mesotrione (Callisto) (Table 6). As per the 2014–2015 survey, the most used POST herbicides in corn were glyphosate, mesotrione/S-metolachlor plus glyphosate, and dicamba/diflufenzopyr (Status) (Sarangi & Jhala, 2018). Despite the increasing number of GR weeds and their widespread occurrence in the United States, growers continue to use glyphosate in row-crop production systems. For example, the USDA-NASS Agricultural Chemical Use Survey reported that in 2015, 85% of soybean [*Glycine max* (L.) Merr.] acres in the United States were treated with glyphosate at a rate of 3.0 kg ha^{-1} (USDA-NASS, 2016), whereas in 2017 and 2020, the percentage of acreage treated with glyphosate was reduced to 77% without any substantial change in the application rate (USDA-NASS, 2018, 2021).

While glyphosate remains the most used POST herbicide in soybean, with the release of dicamba/glyphosate-resistant soybean, dicamba has rapidly become a popular POST herbicide for weed management in dicamba-resistant soybean. Glyphosate was applied to over 85% of soybean-producing ground as reported from the Agricultural Chemical Use Survey in 2015 (USDA-NASS, 2016). The most used POST soybean herbicides after glyphosate and dicamba were glufosinate (Liberty), *S*-metolachlor (Dual II Magnum), and fomesafen (Flexstar), with relative importance points ranging between 0.3 and 1.2 in 2019–2020 survey (data not shown). In a 2014–2015 survey, the most used POST soybean herbicides were glyphosate, fluthiacet-methyl (Cadet), clethodim (Select Max), lactofen (Cobra), imazethapyr/glyphosate (Extreme), and fomesafen (Flexstar) with relative importance point ranging from 0.2 to 0.8 (Sarangi & Jhala, 2018). Inadequate responses for sorghum and wheat POST herbicides were reported in the Northeast district; therefore, results were not included. In the West Central district, 2,4-D, dicamba, and bromoxynil plus pyrasulfotole (Huskie) were the three most used POST herbicides in sorghum, while 2,4-D, atrazine, and dicamba were the highest ranked for the Southeast district (Table 6). Respondents ranked 2,4-D, chlorsulfuron/metsulfuron-methyl, and halauxifen-methyl/florasulam as the top three commonly used POST herbicides in wheat (Table 6). In a 2014–2015 survey, the most used POST wheat herbicides were 2,4-D, metsulfuron-methyl, and triasulfuron (Sarangi & Jhala, 2018).

3.6 | Cost of weed management in glyphosate-resistant crops

With the growing concerns regarding GR weeds in Nebraska, the use of PRE herbicides and more diverse POST herbicide mixes has increased, which has consequentially led to the

TABLE 6 Respondents' ranking of commonly used pre-emergence and post-emergence herbicides in major agronomic crops in a 2019–2020 survey of stakeholders in Nebraska to assess problem weeds and weed management practices in agronomic crops.

	Districts[a]			
Rank	**Northeast**	**Southeast**	**West Central**	**Nebraska[b]**
	Pre-emergence herbicides			
Corn				
1	Acetochlor + clopyralid + mesotrione (2.5)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (1.7)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (2.5)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (1.9)
2	*S*-Metolachlor (1.1)	Atrazine (1.1)	*S*-Metolachlor (1.8)	Acetochlor + clopyralid + mesotrione (1.8)
3	Isoxaflutole + thiencarbazone-methyl (1.0)	Atrazine + *S*-metolachlor + mesotrione (1.0)	Atrazine (1.6)	Isoxaflutole + thiencarbazone-methyl (1.7)
Soybean				
1	Flumioxazin + pyroxasulfone (1.8)	Metribuzin + sulfentrazone (1.6)	Flumioxazin + pyroxasulfone (1.9)	Metribuzin + sulfentrazone (1.3)
2	Sulfentrazone + chloransulam-methyl (1.5)	Chlorimuron-ethyl + flumioxazin + pyroxasulfone (1.1)	Saflufenacil + imazethapyr + pyroxasulfone (1.2)	Flumioxazin + pyroxasulfone (1.3)
3	Chlorimuron-ethyl + flumioxazin + thifensulfuron (0.8)	Sulfentrazone + chlorimuron-ethyl (0.8)	Metribuzin + sulfentrazone (0.9)	Sulfentrazone + chloransulam-methyl (1.2)
Sorghum				
1	Atrazine + *S*-metolachlor + mesotrione (1.9)	Atrazine + *S*-metolachlor + mesotrione (2.7)	Atrazine + *S*-metolachlor + mesotrione (2.4)	Atrazine + *S*-metolachlor + mesotrione (2.3)
2	Atrazine (1.4)	Atrazine (1.3)	Atrazine + *S*-metolachlor (1.2)	Atrazine (1.3)
3	Atrazine + *S*-metolachlor (1.0)	Atrazine + *S*-metolachlor (1.1)	Atrazine (1.1)	Atrazine + *S*-metolachlor (1.0)
	Post-emergence herbicides			
Corn				
1	Glyphosate (1.8)	Glyphosate (2.5)	Glyphosate (1.7)	Glyphosate (2.7)
2	Mesotrione (1.1)	Dicamba + diflufenzopyr (1.5)	Dicamba + diflufenzopyr (1.6)	Dicamba + diflufenzopyr (1.3)
3	Dicamba + diflufenzopyr (0.8)	Mesotrione (1.0)	Acetochlor + clopyralid + mesotrione (0.7)	Mesotrione (1.0)
Soybean				
1	Glyphosate (2.1)	Glyphosate (2.3)	Dicamba (2.2)	Glyphosate (2.3)
2	Dicamba (1.8)	Dicamba (1.9)	Glyphosate (1.9)	Dicamba (2.0)
3	Fomesafen (1.0)	Glufosinate (1.2)	*S*-Metolachlor (0.7)	Glufosinate (1.2)
Sorghum				
1	NA	2,4-D (2.1)	2,4-D (1.8)	2,4-D (1.9)
2	NA	Atrazine (1.1)	Dicamba (1.0)	Dicamba (1.1)
3	NA	Dicamba (0.9)	Bromoxynil + pyrasulfotole (0.6)	Atrazine (0.7)

(Continues)

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TABLE 6 (Continued)

Rank	Districts[a] Northeast	Southeast	West Central	Nebraska[b]
Wheat				
1	NA	2,4-D (1.8)	2,4-D (1.9)	2,4-D (1.7)
2	NA	Chlorsulfuron + metsulfuron-methyl (1.2)	Chlorsulfuron + metsulfuron-methyl (1.1)	Chlorsulfuron + metsulfuron-methyl (1.1)
3	NA	Dicamba (0.9)	Halauxifen-methyl + florasulam (1.0)	Halauxifen-methyl + florasulam (0.8)

Note: Values in parentheses represent the relative importance points, calculated using the equation:
$RP = \sum_{r=1}^{3} \frac{FX}{n}$,
where F is the number of respondents choosing a particular rank (r) for a herbicide, X is the number of problem points (3 for rank #1, 2 for rank #2, 1 for rank #3) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum relative importance points are 3.0.
Abbreviation: NA, not available (respondents did not report the required information).
[a]Sufficient responses were not recorded from the Panhandle district; therefore, data from the Panhandle district were not included in this table.
[b]Collective responses from three districts (Northeast, Southeast, and West Central) were listed under Nebraska.

TABLE 7 Average cost of weed management in glyphosate-resistant crops as reported by stakeholders in a 2019–2020 survey in Nebraska to assess problem weeds and their management practices in agronomic crops.

Crops	Districts Northeast	Panhandle	Southeast	West Central	Nebraska State
Corn ($ ha^{-1})	96 (16–198)	93 (42–178)	99 (30–185)	141 (30–198)	101 (16–198)
Soybean ($ ha^{-1})	115 (30–247)	NA	113 (30–296)	154 (30–257)	115 (30–296)
Alfalfa ($ ha^{-1})	33 (17–74)	NA	44 (12–74)	40 (15–68)	41 (12–74)

Note: Responses of growers and crop consultants were both considered. Values in parentheses indicate the min to max range of the cost.
Abbreviation: NA, not available (respondents did not report).

increased cost of weed management. Along with the increased diversification of chemical control programs, tillage and cover crops have been used in conjunction with chemical control. Averaged across districts, the cost of weed management in GR corn and soybean was $101 and $115 ha^{-1}, respectively (Table 7). In a survey conducted in 2014–2015, the cost of weed management in corn was $90 and $81 for soybean (Sarangi & Jhala, 2018). A higher cost is due to the increased cost of herbicides and their application cost including fuel.

3.7 | Herbicide-resistant weed management

3.7.1 | The problem of herbicide-resistant weeds

Results indicated that 80% of growers in Nebraska suspected the presence of at least one herbicide-resistant weed species on their farms. In a survey conducted in 2014–2015, 60% of respondents reported the presence of at least one herbicide-resistant weed in their fields (Sarangi & Jhala, 2018). Respondents were asked to rate the problem of herbicide-resistant weeds on a scale of 0–10, with 0 meaning not at all a problem and 10 meaning highly problematic (Question 3.1 in Appendix). Averaged across districts, respondents indicated a high concern (average score of 8.1 with a median 8.3) about the problem of GR weeds in Nebraska (Figure 2). In the West Central district, respondents rated GR weeds as their biggest problem (average score of 8.9 with a median 9.2) compared to other districts, which could be explained by the results showing that weeds such as GR Palmer amaranth were the highest ranked in this district (Table 4). Palmer amaranth is well documented as a major challenge in row crop agriculture in recent times. Several studies have shown that the extended emergence pattern of Palmer amaranth can create major hurdles in management (Jha & Norsworthy, 2009), and it has been recommended that mixing residual herbicide such as acetochlor or pyroxasulfone with a POST herbicide can aid in management by providing overlapping residual activity (Hartzler et al., 2004;), particularly in non-genetically modified organism conventional soybean (Sarangi & Jhala, 2019).

A total of 32% of growers in Nebraska responded positive toward rotating GR crops with non-GR crops (Table 7). Unique out of all other districts, respondents in the Panhandle district showed that growers are more likely (68%) to rotate GR crops with non-GR crops compared to other

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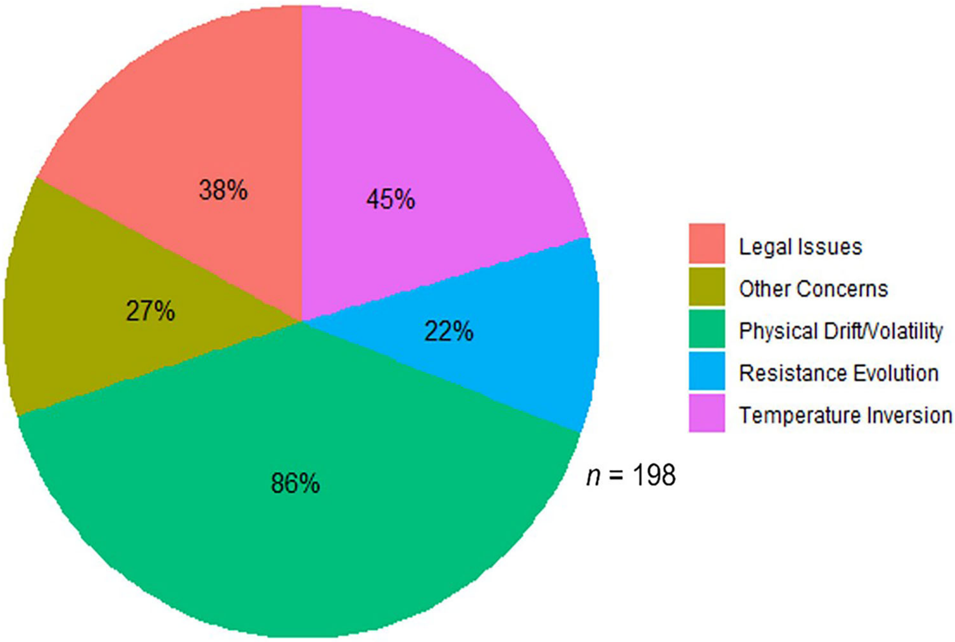

FIGURE 2 Percent of respondents expressing concerns about the adoption of new crops resistant to multiple herbicides.

districts, which showed a range of 28%-33%. Survey results indicated that the highest crop diversity (56.6% of total farmed or scouted areas under crops other than corn and sugarbeet) was reported in the Panhandle district (Table 2), which was believed to have led to the highest percentage of non-GR crops being planted in this district due to crop diversity.

3.7.2 | Field scouting and late-season weed control

Scouting for weeds both prior to and after herbicide application is a key tenant of an integrated weed management program (Norsworthy et al., 2012; Young, 2017). Averaged across districts, 95% of respondents reported that they either have scouted or advised scouting farms before and after herbicide application (Table 8). In the Panhandle district, half of respondents (51%) controlled weed escapes late in the season. In contrast to the Panhandle district, 71%–77% of growers reported practicing late-season weed management in the other three districts (Table 8). Late-season weed escapes can often be disregarded by growers, as they require extra labor and rarely affect crop yields; however, the long-term biological, ecological, and economic benefits of late-season weed management cannot be overlooked. Several weed species, such as waterhemp and Palmer amaranth, exhibit a prolonged emergence pattern (Hartzler et al., 2004; Jha & Norsworthy, 2009), and delayed emergence can lead to late-season weed escapes, as most POST herbicide applications in row crops are made early in the season and have residuals that last only partway through the growing season. Mechanical and/or manual weed management was practiced by 17% of respondents for late-season weed control (data not shown).

3.7.3 | Use of herbicides with multiple sites of action

A statewide survey showed a high degree of familiarity with herbicide sites of action (SOA), with 93% using at least two SOAs in their herbicide programs (Table 8). The high prevalence of ALS inhibitor-resistant and GR weeds in Nebraska was likely a major contributor to growers using herbicides with multiple SOAs. In crops such as corn, a major contributor to diversifying herbicide SOAs can be attributed to commonly used PRE and POST herbicides being premixes of different SOAs (Table 6). Similarly in soybean, use of a PRE herbicide with multiple effective SOAs is required as a foundation for the early season management of multiple herbicide-resistant Palmer amaranth (Mausbach et al., 2021).

3.7.4 | Adoption of new multiple herbicide-resistant crops

Survey results showed that 77% of respondents were aware of new multiple herbicide-resistant crops that have come to the market or are set to be released soon (Table 8). Similarly, 89% of the respondents in Nebraska were aware of the multiple herbicide-resistant crop technologies in a 2014–2015 survey (Sarangi & Jhala, 2018). Along with awareness of new herbicide-resistant crops is the willingness to adopt

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TABLE 8 Respondents' knowledge and perception of management strategies for controlling herbicide-resistant weeds in a 2019–2020 survey of stakeholders in Nebraska to assess problem weeds and their management practices in agronomic crops.

Glyphosate-resistant weed management questions	Districts[a]				
	Northeast	Panhandle	Southeast	West Central	Nebraska
Average problem ratings for the weeds resistant to glyphosate (on a scale of 1–10)	7.5 (0.2)	7.3 (0.7)	8.3 (0.4)	8.9 (0.4)	8.1 (0.2)
Glyphosate-resistant crops rotated with crops not resistant to glyphosate (% of total growers)	30	68	33	28	32
Percentage of respondents that suspect herbicide-resistant weeds	84	94	90	98	88
Percentage of respondents scouted/advised to scout farms before and after herbicide applications[a]	98	90	93	97	95
Percentage of growers controlled weed escapes or prevented seed set later in the season	75	51	71	77	72
Percentage of respondents familiar with the herbicide site of action	92	84	94	96	93
Percentage of growers using multiple SOAs in their herbicide programs	94	90	93	94	93
Percentage of respondents aware of new crops resistant to multiple herbicides	87	64	79	77	77
Percentage of respondents concerned with drift issues arising from new herbicide resistant crops	55	58	71	62	63

Note: Values in parentheses represent the standard error of the mean.
Abbreviation: SOAs, sites of action.
[a]Respondents for this question include only growers and crop consultants.

new technologies. Of the survey respondents, 67% noted a willingness to adopt new crop technologies a year or two after product release (data not shown) compared with only 45% of respondents showing no concerns regarding the adoption in the 2014–2015 survey (Sarangi & Jhala, 2018). Since the commercial release of dicamba/glyphosate-resistant soybean (Roundup Ready 2 Xtend) in 2017, off-target dicamba injury issues have become a significant concern for stakeholders, with 86% of respondents reporting physical drift/volatility concerns (Figure 2). Off-target movement of synthetic auxins has been of increasing concern, as a survey from the southern United States in 2011 reported that 77% of crop consultants were concerned with off-target movement of synthetic auxins with the adoption of synthetic auxin-resistant crops (Riar, Norsworthy, Steckel, Stephenson, & Bond, 2013; Riar, Norsworthy, Steckel, Stephenson, Bond, Eubank, et al., 2013). A major portion of respondents (38%) indicated a growing concern with legal issues specifically regarding synthetic auxin herbicides such as dicamba and 2,4-D. Given the relative proximity of sensitive crops to mid-season applications of dicamba and 2,4-D, survey respondents noted a growing concern about disputes between neighbors. Survey responses showed that the off-target movement of 2,4-D/dicamba is of major interest and concern to stakeholders, with 45% looking for education about proper application and identifying the signs of temperature inversions (Figure 2). Along with a major concern about issues related to synthetic auxin herbicides, 22% of survey respondents had concerns that new technologies may lead to reliance on a small handful of herbicides used in POST applications, leading to the evolution of herbicide-resistant weeds (Figure 2). A variety of other concerns were reported, with 27% of respondents expressing concerns such as application technologies associated with new herbicide-resistant crops, market issues, and extension/research concerns.

3.7.5 | Weed management research and extension priorities

Survey participants were directed to list research and extension priorities to improve future weed management in

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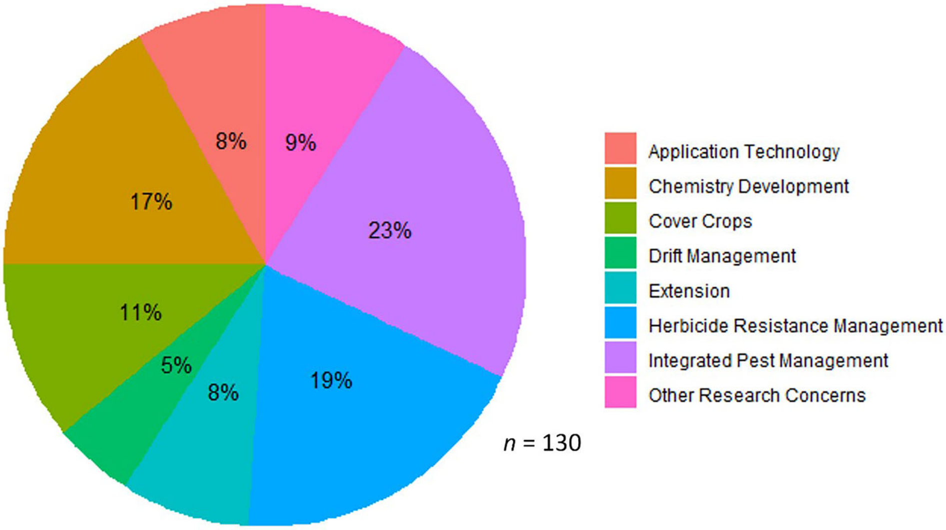

FIGURE 3 Future weed science research and extension priorities identified by survey respondents.

Nebraska (Question 4 in Appendix). Of the 130 responses, the largest portion (23%) indicated the need for integrated pest management research conjoining chemical control options with other biological and mechanical management methods (Figure 3). Few survey participants (17%) noted that additional herbicide SOAs are needed to control the increasing number of multiple herbicide-resistant weeds in row crops along with testing new herbicide premix formulations. Other areas highlighted by respondents as their top priorities were research areas in application technology, cover crops, and herbicide drift management (Figure 3). Similar priorities have been listed by respondents in a 2014–2015 survey (Sarangi & Jhala, 2018).

4 | CONCLUSIONS

Palmer amaranth was ranked as the most problematic weed in the 2019–2020 survey which was at the sixth rank in the 2014–2015 survey. This is because of many factors including the evolution and widespread occurrence of herbicide-resistant Palmer amaranth across the state, multiple and wide window of emergence, high genetic diversity, and ability to produce seeds, and dioecious reproductive biology increases the chances of pollen-mediated gene flow and spread of herbicide resistance. There were some differences between two surveys for the most applied preplant, PRE and POST herbicides in corn, soybean, sorghum, and wheat as well as in management practices. Dicamba was listed as the third most applied preplant burndown herbicide and the second most used POST herbicide in soybean in the 2019–2020 survey compared with no listing of them in the 2014–2015 survey. This is because of the widespread adoption of dicamba-resistant soybean and use of dicamba for the management of GR horseweed for preplant burndown application, and GR Palmer amaranth and waterhemp control in POST applications.

AUTHOR CONTRIBUTIONS

Shawn T. McDonald: Conceptualization; data curation; formal analysis; methodology; writing—original draft. **Debalin Sarangi**: Validation; writing—review and editing. **Jennifer M. Rees**: Data curation; methodology; resources. **Amit J. Jhala**: Conceptualization; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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APPENDIX

A CONDENSED VERSION OF THE SURVEY QUESTIONNAIRE USED IN THE 2019–2020 SURVEY OF STAKEHOLDERS IN NEBRASKA TO ASSESS PROBLEM WEEDS AND THEIR MANAGEMENT PRACTICES IN AGRONOMIC CROPS.

General information
Please best describe your primary occupation. Which county and state are you from?
Section 1. Crop Production and Problem Weeds
1.1 How many acres did you farm/scout in 2019? How many of these acres were under tillage and no-till production?
1.2 How many acres (farmed/scouted) were under different crops (corn, dry edible beans, grain sorghum, soybean, sugar beet, wheat, and others)?
1.3 What are the five most difficult-to-control weeds in your opinion? Please write them in order, where #1 is the weed most difficult to control. 1. _________; 2. _________; 3. _________; 4. _________; 5. _________
1.4 Which herbicide-resistant weeds do you suspect on your farm/scouted areas, or are you concerned about them in the future? What are the resistances you suspect? Do you have any glyphosate-resistant weeds on your farm/scouted areas? Please list them. Suspected herbicide-resistant weeds: ________; Resistant to (herbicide name): ________
1.5 How many acres of each crop did you farm/scout in 2019? Conventional Corn: ________ Convention Soybean: ________ Herbicide-resistant Corn: ________ Herbicide-resistant Soybean: ________

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General information
Section 2: Herbicide usage
2.1 Do you use preplant burndown herbicides? Please list the three most common preplant burndown herbicides in order, where #1 is the most used herbicide. 1._________; 2._________; 3._________
2.2 Do you use pre-emergence (soil residual) herbicides? Please list the three most common pre-emergence herbicides in order, where #1 is the most used herbicide. Corn: 1._________; 2._________; 3._________ Soybean: 1._________; 2._________; 3._________ Wheat: 1._________; 2._________; 3._________ Others (_____): 1._________; 2._________; 3._________
2.3 Do you use post-emergence herbicides? Please list the three most common post-emergence herbicides in order, where #1 is the most used herbicide. Corn: 1._________; 2._________; 3._________ Soybean: 1._________; 2._________; 3._________ Wheat: 1._________; 2._________; 3._________ Others (_____): 1._________; 2._________; 3._________
2.4 What is your average cost (per acre) of weed control in roundup ready (glyphosate-resistant) crops?
Section 3: Glyphosate-resistant weed management
3.1 How serious is the weed resistance to glyphosate? Answer using a scale of 1–10 where 1 is “not at all serious” and 10 is “very serious.”
3.2 Do you rotate between roundup ready and non-roundup ready crops?
3.3 Do you scout field before and after herbicide applications?
3.4 Do you control weed escapes or prevent seed set later in the season? Yes: ______ No: ______ If yes, with which methods (chemical, mechanical, or manual control methods): ________
3.5 How familiar are you with herbicide sites of action (1–10, 1 is “not well known” and 10 is “well known”)?
3.6 Are you aware of new multiple herbicide-resistant crops such as Alite 27/LibertyLink soybean (glufosinate-, glyphosate-, and isoxaflutole-resistant) and XtendFlex soybean (dicamba-, glufosinate-, and glyphosate-resistant)? Yes: ________ No: ________
3.7 Do you have any concerns such as volatility or drift hazards, with the adoption of newly released herbicide resistant crops? Please list them. 1. ________; 2. ________; 3. ________
Section 4: Weed management research and extension priorities
4.1 What are your future research and extension needs/expectations from the University of Nebraska-Lincoln’s weed scientist and experts? 1. ________; 2. ________; 3. ________

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