The cost of implementing effective herbicide mixtures for resistance management

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Abstract: Background: Mixtures of herbicide sites of action (SOA) are often promoted as an effective practice for proactive herbicide resistance management, but the cost of implementation is less-often considered in these recommendations, especially in the academic literature.

Objective: Estimate the costs of implementing herbicide SOA mixtures that are effective for herbicide resistance management under different scenarios involving crops, weed species, and existing resistance.

Methods: Using data from the Guide for Weed, Disease, and Insect Management in Nebraska, an optimization function was used to find the lowest cost for effective weed control (single herbicide providing ≥90%), and effective resistance management (at least 2 SOA providing ≥90%) under various crop, weed, and herbicide resistance scenarios.

Results: In corn and soybean, effective SOA mixtures for waterhemp and Palmer amaranth increased herbicide costs at least 2-fold compared to herbicide costs that provided effective weed control with a single SOA. Resistance to certain SOA had greater impact on the cost of effective herbicide mixtures; in corn, resistance to SOA Group 5 or Group 9 herbicides caused the greatest increase in mixture costs, whereas in soybean Group 9 or Group 14 resistance caused the greatest increase in mixture costs. In dry edible bean, effective mixtures were at least 5 times more expensive than similar scenarios in soybean, and in several scenarios, there were no herbicide mixtures available that met effective resistance management criteria.

Conclusions: The use of effective herbicide SOA mixtures has sound scientific basis for slowing the evolution of herbicide resistance, but the cost of implementation is a major barrier for widespread adoption even in fields where herbicide resistance is not yet present.

Keywords: economics; proactive resistance management

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1. Introduction

Production of most field crops has become heavily reliant on herbicides, and long-term overreliance on herbicides as the main weed management tool has resulted in a continuous increase in the evolution of herbicide-resistant weed populations (Heap, 2021; Kniss, 2018). The primary cause of herbicide resistance is the recurrent application of highly effective herbicides of the same site of action (SOA) (Gressel, 1978; Conard, Radosevich, 1979; Beckie, 2006). Recommendations for proactive and reactive herbicide-resistant weed management are therefore aimed at reducing the reliance on a single herbicide SOA, therefore reducing the selection pressure. Herbicide selection pressure can be reduced by diversifying crop rotations, incorporating cover crops, altering cultural practices to influence crop competitiveness, increasing the intensity of tillage, and by using effective herbicide SOA mixtures (Beckie, 2006; Norsworthy et al., 2012).

It is known that crop rotations do not eliminate weeds but can be used to reduce the build-up of weed populations, including herbicide-resistant weeds. However, the effectiveness of rotational crops in managing herbicide-resistant weeds depends on their competitiveness against the target weed, planting and harvesting time relative to the weed, and the number and efficacy of herbicides registered for use in the crop (Sbatella et al., 2019; Mosqueda et al., 2020). Thus, even in diverse crop rotations, effective herbicides still play a critical role in herbicide resistance management. It is, therefore, not surprising that using effective herbicide mixtures is one of the commonly recommended practices for managing herbicide-resistant weeds (Abbas et al., 2016; Mosqueda et al., 2020).

From a biological standpoint, mixtures are supported by both theory and empirical data (Gressel, 1978; Beckie, Reboud, 2009; Evans et al., 2016). The use of mixtures of diverse SOA is based on the principle that weeds are exposed to multiple herbicide SOAs simultaneously, thereby reducing the selection pressure on an individual target site (Beckie, 2006; Kniss, 2018). In addition, mixtures deplete resistance alleles, thereby decreasing the chance of survival of all individuals (Evans et al., 2016). In fact, field studies have demonstrated that using effective herbicide mixtures can delay the evolution of herbicide resistance (Beckie, Reboud, 2009; Evans et al., 2016). Despite the demonstrated effectiveness of herbicide mixtures in delaying herbicide resistance, farmers rarely use herbicide mixtures as a proactive resistance management strategy (Beckie, 2006). Low adoption of herbicide mixtures might be due to a myriad of factors, and it is a decision likely driven by short-term economic returns (Weirich et al., 2011; Riar et al., 2013; Hurley, Frisvold, 2016). Orson (1999) pointed out that farmers are businessmen who make decisions in the context of their own enterprises. Thus, unless they can be convinced that herbicide-resistant weeds will significantly affect their profits, they will not adopt any proactive measures to delay the evolution of herbicide resistance (Orson, 1999). A benchmark study found that weed control costs were about 31% higher for best management practices recommended by academics compared to standard practices used by farmers (Edwards et al., 2014).

For herbicide mixtures to be effective at managing resistance, the herbicides must not only have different SOAs, but also be similarly effective and persistent, allowing them to act simultaneously on the same weed cohorts (Norsworthy et al., 2012). Therefore, effective herbicide mixtures tend to be expensive and cumbersome to develop and implement. Here, we estimate the costs associated with using effective herbicide mixtures under different scenarios in corn (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.), and dry edible bean (*Phaseolus vulgaris* L.), and compare the cost of effective mixtures with the cost to achieve effective weed control with a single SOA.

2. Materials and Methods

All commercially available herbicide products (N=128) registered in the state of Nebraska and included in the Guide for Weed, Disease, and Insect Management in Nebraska (Knezevic et al. 2020) for broadleaf weed control in corn (N=67), soybean (N=67), or dry edible bean (N=16) were included as potential herbicides in this analysis. For each commercial herbicide product, efficacy data were estimated using a 1 to 10 scale (Table 1) for each active ingredient on each weed species. Efficacy ratings were developed by local experts based on herbicide label statements and local and regional efficacy research. Approximate cost per hectare was calculated using product costs published in Knezevic et al. (2020), where dozens of pesticides distributors within the state of Nebraska are surveyed annually for the cost of each pesticide. Prices reported by Knezevic et al. (2020) are an average of all surveyed pesticide distributors, and only reflect the approximate cost of each product, not the costs of applying the product. Reported costs assume no manufacturer marketing incentive programs were available. While these herbicide costs are likely not accurate for all regions or economic conditions, they are likely to be representative of relative costs for many regions and years.

An optimization function was used to find the lowest herbicide cost for various crop, weed, and herbicide resistance scenarios. A scenario included a crop (corn, soybean, or dry edible bean), weed species (Palmer amaranth, waterhemp, or kochia), and pre-existing herbicide resistance. Within each scenario, the optimization function identified the lowest cost herbicide option that (1) provided effective weed control; and (2) provided an effective herbicide mixture. Effective weed control was defined as providing at least one herbicide that provided a weed control efficacy rating of ≥9 for all weed species in the scenario. An effective mixture was defined as providing at least two herbicide SOA that provided weed control efficacy ratings of ≥9 for all weed species in the scenario. If, within a scenario, effective weed control or an effective mixture could not be found, the weed control efficacy rating criteria was lowered until the other criteria were met, and this reduced efficacy rating is noted.

Table 1 - Weed control efficacy rating and the corresponding expected weed control from the Guide for Weed, Disease, and Insect Management in Nebraska (Knezevic et al., 2020)

Expected weed control	Weed control efficacy rating
≥96%	10
91 to 95%	9
86 to 90%	8
80 to 85%	7
70 to 79%	6
60 to 69%	5
<60	0 to 4

For the purposes of defining effective weed control and effective mixtures, we assumed that a single application of the selected herbicide(s) were sufficient, regardless of herbicide characteristics such as residual activity or PRE vs POST application timing. This assumption is unlikely to be realistic under field conditions due to emergence patterns of various weeds, and thus the economic estimates presented here should be considered very conservative. Actual costs for effective weed control and effective mixtures will nearly always be greater than the estimates provided here, especially for more complex scenarios involving multiple weed species and multiple herbicide resistance. We also assumed no herbicide interactions (synergism or antagonism) between components of the mixtures.

3. Results and Discussion

Scenario 1: Palmer amaranth control in corn. In corn, if no pre-existing herbicide resistance was present, Palmer amaranth (*Amaranthus palmeri* S. Watson) could be effectively controlled for $7.41/ha by spraying glyphosate (Table 2). An effective herbicide SOA mixture included glyphosate plus atrazine, and cost $15.44/ha, just over twice as expensive. The herbicides atrazine and glyphosate are among the most commonly used herbicides in corn

(Kniss, 2018) and are relatively inexpensive compared to other available broad-spectrum herbicides. Because the two herbicides providing the least expensive effective herbicide mixture were SOA Group 5 and Group 9 herbicides, single resistance to other herbicide SOA (like SOA Group 2) had no impact on the minimum cost of weed control or the minimum cost of effective mixtures. Singular resistance to Group 5 or Group 9 herbicides had minimal impact on the cost to obtain effective weed control, since both atrazine and glyphosate are relatively low-cost options. Although the cost to obtain effective weed control was not substantially increased from resistance to any single herbicide SOA, resistance to either Group 5 or Group 9 herbicides increased the cost of an effective mixture to $24.70 to $25.32/ha, over three times as much compared to the cost of obtaining effective weed control, and a 60% increase in the cost of an effective mixture compared to where no herbicide resistance was present in Palmer amaranth.

Multiple resistance to the Group 5 and Group 9 herbicides more than doubled the cost of effective Palmer amaranth control compared to no pre-existing resistance ($7.41 to $17.29/ha) and increased the cost of an effective mixture three-fold ($15.44 to $47.55/ha) compared to no pre-existing resistance. An effective mixture for four-way resistance to SOA Groups 2, 5, 9, and 14 cost at least $70.89/ha, more than 4.5-times greater than an effective mixture where no resistance exists.

Scenario 2: Waterhemp control in soybean. Similar to corn, any single SOA resistance had no major impact on the cost to obtain effective waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer) control in soybean (Table 3). The least expensive product that provided waterhemp control in this analysis was a pre-mix of sulfentrazone (Group 14) and cloransulam-methyl (Group 2) even though cloransulam-methyl does not provide effective control of waterhemp. For some weed species, this product would represent an effective mixture, but not for the species selected for this analysis. Glyphosate is a similarly low-priced option, making it inexpensive to obtain weed control. An effective SOA mixture approximately doubled the cost when no resistance was present or if SOA Group 2 resistant waterhemp was present. Resistance to either Group 9 or Group 14 herbicides increased the cost of an effective mixture by 25%.

Multiple resistance to 2 SOAs (group 2 + 9 or group 2 + 14) in waterhemp did not substantially increase the cost of effective waterhemp control. However, multiple resistance in waterhemp increased the cost of an effective mixture nearly five-fold, to over $39/ha, compared to waterhemp with no pre-existing resistance (Table 3). Three-way multiple resistance to Groups 2, 9, & 14 increased the cost of effective waterhemp control nearly four-fold ($30.88/ha) and the cost of an effective mixture nearly eight-fold ($64.38/ha). Herbicides in Groups 2, 9, & 14 represent a substantial portion of the commonly used herbicides in soybean (Kniss, 2018), and resistance to these SOA is widespread in the US (Heap, 2021).

Scenario 3: Palmer amaranth and kochia control in corn. Growers rarely deal with a single problematic weed species in their fields, and therefore, proactive management requires simultaneously targeting multiple weed species with potential to evolve herbicide resistance. Having multiple weeds with resistance to commonly used herbicides further complicate finding effective weed control options. In this scenario, we evaluated just two weed species (Palmer amaranth and kochia (*Bassia scoparia (L.)* A. J. Scott)) that are problematic in the central Great Plains region of the United States. In corn, the cost of effective Palmer amaranth and kochia control with no pre-existing herbicide resistance is $7.41/ha, which is

Table 2 - Cost of effective Palmer amaranth control under different herbicide resistance scenarios in corn

Scenario	Cost for effective weed control	Cost of effective mixture
	--------------US $/ha--------------	
Corn, Palmer amaranth, no resistance	7.41	15.44
Corn, Palmer amaranth, Group 5 resistance	7.41	24.70
Corn, Palmer amaranth, Group 9 resistance	8.03	25.32
Corn, Palmer amaranth, Group 5 & 9 resistance	17.29	47.55
Corn, Palmer amaranth, Group 5 & 14 resistance	7.41	24.70
Corn, Palmer amaranth, Group 2 & 9 resistance	8.03	38.29
Corn, Palmer amaranth, Group 2, 5, 9, & 14 resistance	33.35	70.89

Table 3 - Cost of effective waterhemp control under different herbicide resistance scenarios in soybean

Scenario	Cost for effective weed control	Cost of effective mixture
	--------------US $/ha--------------	
Soybean, waterhemp, no resistance	8.25	16.90
Soybean, waterhemp, Group 2 resistance	8.25	16.90
Soybean, waterhemp, Group 9 resistance	8.25	21.22
Soybean, waterhemp, Group 14 resistance	8.65	21.62
Soybean, waterhemp, Group 2 & 14 resistance	8.65	39.53
Soybean, waterhemp, Group 2 & 9 resistance	8.25	39.13
Soybean, waterhemp, Group 2, 9, & 14 resistance	30.88	64.38

the same as the cost of controlling Palmer amaranth or kochia alone (Table 4). The cost of an effective mixture for both species is similarly unchanged compared to either species alone ($15.44/ha) as long as there is no pre-existing resistance. Glyphosate resistance (SOA Group 9) has minimal impact on the cost of weed control (increasing the cost by $0.62/ha), but increases the cost of an effective mixture to over $55/ha. Atrazine resistance (SOA Group 5) has a similar effect. Multiple resistance to Group 5 and Group 9 herbicides increases the cost of weed control approximately 6-fold, and increases the cost of an effective SOA mixture over 7-fold ($114.98/ha) compared to no pre-existing herbicide resistance.

Scenario 4: Waterhemp and kochia control in soybean. Waterehemp and kochia resistance to either 1 or 2 herbicide SOA did not increase the cost to obtain effective weed control (Table 5). Resistance to SOA Group 2 had less impact on the cost of effective mixtures ($16.90/ha, same as for no existing resistance) compared to either SOA Group 9 or SOA Group 14 ($32/ha, nearly twice the cost as where no resistance exists). Multiple resistance to glyphosate and ALS inhibitors did not increase the cost of effective weed control, but further increased the cost of an effective mixture to $50.25/ha. Three-way SOA resistance to glyphosate, ALS, & PPO inhibitors increased the cost of waterhemp + kochia control 5-fold to $42/ha, and increased the cost of an effective mixture 12-fold to over $100/ha.

Scenario 5: Palmer amaranth and kochia control in dry edible bean. Corn and soybean represent crops with a substantial number of available herbicides; most crops grown in the Central Great Plains (and elsewhere) have far fewer registered herbicide options (Adjesiwor et al., 2020; Soltani et al., 2018). As an example, we evaluated the cost of weed control and effective mixtures in dry edible bean. In the absence of herbicide resistance, the cost of effective Palmer amaranth control, with or without kochia present, was $17.91/ha (Table 6). The least expensive herbicide for control of these two species was fomesafen, a SOA Group 14 herbicide. Thus, even without herbicide resistance, the cost of effective weed control in dry edible bean was approximately double that of corn or soybean. While resistance to group 2 herbicides did not increase the cost of

Table 4 - Cost of effective Palmer amaranth and kochia control under different herbicide resistance scenarios in corn

Scenario	Cost for effective weed control	Cost of effective mixture
	--------------US $/ha--------------	
Corn, Palmer amaranth, no resistance	7.41	15.44
Corn, kochia, no resistance	7.41	15.44
Corn, Palmer amaranth & kochia, no resistance	7.41	15.44
Corn, Palmer amaranth & kochia, Group 9 resistance	8.03	55.70
Corn, Palmer amaranth & kochia, Group 5 resistance	7.41	55.08
Corn, Palmer amaranth & kochia, Group 5 & 9 resistance	47.67	114.98

Table 5 - Cost of effective waterhemp and kochia control under different herbicide resistance scenarios in soybean

Scenario	Cost for effective weed control	Cost of effective mixture
	--------------US $/ha--------------	
Soybean, waterhemp, no resistance	8.25	16.90
Soybean, kochia, no resistance	8.25	16.90
Soybean, waterhemp & kochia, no resistance	8.25	16.90
Soybean, waterhemp & kochia, Group 9 resistance	8.25	32.34
Soybean, waterhemp & kochia, Group 2 resistance	8.25	16.90
Soybean, waterhemp & kochia, Group 14 resistance	8.65	32.74
Soybean, waterhemp & kochia, Group 2 & 9 resistance	8.25	50.25
Soybean, waterhemp & kochia, Group 2, 9, & 14 resistance	42.00	103.89

Table 6 - Cost of effective Palmer amaranth and kochia control under different herbicide resistance scenarios in dry edible bean

Scenario	Cost for effective weed control	Cost of effective mixture
	--------------US $/ha--------------	
Dry bean, Palmer amaranth, no resistance	17.91	45.70
Dry bean, Palmer amaranth, Group 2 resistance	17.91	55.58[a]
Dry bean, Palmer amaranth, Group 14 resistance	27.79	65.46[a]
Dry bean, Palmer amaranth, Group 2 & 14 resistance	32.11	69.78[b]
Dry bean, Palmer amaranth & kochia, no resistance	17.91	45.70[a]
Dry bean, Palmer amaranth & kochia, Group 2 resistance	17.91	85.22[a]
Dry bean, Palmer amaranth & kochia, Group 14 resistance	27.79	95.10[a]
Dry bean, Palmer amaranth & kochia, Group 2 & 14 resistance	32.11	99.42[b]

[a] No effective mixtures with efficacy ratings ≥ 9; this mixture does not meet full criteria for effective resistance management.

[b] No effective mixtures with efficacy ratings ≥ 8; this mixture does not meet full criteria for effective resistance management.

effective Palmer amaranth and kochia control, resistance to group 14 herbicides increased the cost of effective Palmer amaranth and kochia control to $27.79 (Table 6).

Without any pre-existing herbicide resistance, the least expensive mixture for proactive resistance management for Palmer amaranth was $45.70/ha, which was more than 2.5-fold more expensive compared to the cost to obtain effective Palmer amaranth control (Table 6). If Palmer amaranth had Group 2 or Group 14 resistance, then there were no herbicide mixtures that met the efficacy criteria for an effective SOA mixture for resistance management, because there are a limited number of herbicides labeled for weed control in dry edible bean. Aside from group 2 and 14 herbicides, there are only three other herbicides groups (SOA Group 3, 6, and 15) available for broadleaf weed control in dry edible bean (Knezevic et al., 2020). Therefore, the remaining mixture costs shown in Table 6 are for mixtures that are less effective for delaying resistance, as the second herbicide SOA does not provide sufficient efficacy on Palmer amaranth. Even so, these less effective mixture increased the cost of Palmer amaranth mixtures to $55.58 to $65.46/ha. If Group 2 resistant Palmer amaranth and Group 2 resistant kochia are present (not uncommon in the Central Great Plains), then a SOA mixture will cost at least $85/ha, and yet will not provide sufficient efficacy to maximize proactive resistance management.

4. Conclusions

Previous studies have shown that herbicide resistance best management practices, including effective herbicide mixtures, tend to be more expensive than standard weed control practices (Weirich et al., 2011; Wilson et al., 2011; Edwards et al., 2014). However, we are unaware of previous work that rigorously evaluated the additional cost of herbicide mixtures that meet resistance management efficacy criteria for specific crop and weed scenarios. In this work, we show that in corn, soybean, and dry edible bean, an effective SOA mixture will *at least* double the cost of herbicides even if no pre-existing herbicide resistance is present. This cost will increase even further if resistance to herbicides already exists in a field. Although herbicide mixtures are undoubtedly effective for proactive resistance management, it is difficult to imagine a majority of growers doubling the cost of herbicides for their operation to manage a problem that they do not yet have. Thus, sole reliance on herbicide mixtures as a proactive herbicide resistance management strategy is extremely unlikely.

The impact of herbicide resistance on the cost of effective weed control and the cost of effective herbicide mixtures depends heavily on the number of herbicides labeled for use in the crop. In corn and soybean, there are numerous herbicide options that can provide effective control of multiple weed species. Crops with smaller global acreage, such as dry edible bean, sugar beet, cotton, and many others tend to have fewer herbicide options. This means that herbicide mixtures that meet efficacy criteria for proactive resistance management may not be available (Sbatella et al., 2019), and if they are, may be even more cost-prohibitive. This should be taken into account when developing weed management recommendations. Much of the research on management of herbicide-resistant weeds is focused on major crops like corn and soybean (e.g. Livingston et al., 2016). While useful for the large area of corn and soybean production, the conclusions from that work are less relevant to other crops where herbicide options are far more restrictive, or on farms where a more diverse cropping system is desired.

Finding effective SOA mixtures against weeds that have already evolved resistance to many of the previously effective herbicide options is a continuing, and costly, challenge (Evans et al., 2016). While proactive herbicide resistance management is more expensive in the short to medium term, it has been proposed that reactive resistance management would be even more expensive (Livingston et al., 2016) as multiple resistance evolves. Previous analyses suggesting long-term financial benefits from proactive adoption of herbicide mixtures, however, have not documented the efficacy of the mixtures selected. Livingston et al. (2016), for example, focused primarily on observed changes in weed density and the resulting effect on yield functions and revenue. This is a reasonable approach, but the herbicide mixtures evaluated do not meet efficacy criteria for effective SOA mixtures for their target weed (horseweed, *Conyza canadensis*). It is difficult to say, then, whether that work has accounted properly for the appropriate costs (it is certainly plausible that an effective mixture would have similar costs, and so their economic results may still be an accurate reflection). A full, accurate accounting of the cost of proactive resistance management practices and the longer-term implications will be important in convincing farmers to use proactive measures to delay the evolution of herbicide resistance (Orson, 1999).

Herbicides will undoubtedly remain an important weed management tool well into the future, even where there is wide-scale or multiple resistant weeds. For example, in a survey, Riar et al. (2013) found that multiple SOAs were adopted on 68% of cotton (*Gossypium* L.), 67% of soybean, and 85% of rice (*Oryza sativa* L.) fields. Greater adoption of multiple SOAs on rice fields was attributed to barnyardgrass (*Echinochloa crus-galli (L.)* P. Beauv.) biotypes with evolved resistance to commonly used herbicides in rice. Prince et al. (2012) reported that 54 to 61% of farmers use multiple SOAs and residual or additional postemergence herbicides to manage glyphosate-resistant weeds. Kniss (2018) showed similar trends in cotton and soybean, where herbicide SOA diversity decreased rapidly in the United States as glyphosate-resistant crop cultivars were adopted, then increased as glyphosate-resistant weed species evolved. Thus, history suggests that herbicide mixtures are adopted in *reaction* to evolved resistance, and not proactively to delay the evolution of resistance. The substantial increase in costs shown here are a likely contributing reason for the lack of proactive adoption of effective herbicide mixtures.

Although empirical data and modeling support herbicide SOA mixtures as an effective management strategy for most target-site herbicide resistance mechanisms, mixtures may be less effective for metabolic resistance mechanisms. Comont et al. (2020) even suggest that herbicide mixtures were associated with an *increase* in non-target site resistance. Even if the cost of herbicide mixtures were affordable to all growers, the potential increase in non-target site resistance may limit the long-term benefit of this practice.

Given the high cost, low adoption, and potentially limited benefit of proactive herbicide mixtures, non-herbicide and integrated weed control practices such as crop rotation, mechanical weed control, cover/smother crops etc., will need to play a critical role in both proactive and reactive herbicide resistance management, especially in small acreage crops like dry edible bean. These practices cannot typically provide complete weed control throughout the growing season, and often must be used in combination. For example, residual herbicides are often combined with cover crops to provide effective weed control (Osipitan et al., 2019).

Combining effective herbicide mixtures into more complex cropping systems that employ other resistance management strategies presents other challenges. Many of the herbicides selected to provide effective SOA mixtures in corn and soybean have soil residual activity and crop rotation restrictions to many crops. For example, the combination of sulfrentrazone plus cloransulam-methyl that provided low-cost effective weed control in soybean would preclude planting of corn for up to 18 months (in low organic matter or high pH soils common in the US Great Plains), sugar beets for 30 months, and canola for 24 months. If these or other susceptible crops are part of the crop rotation, then the cost of an effective herbicide mixture will increase substantially. Atrazine, an inexpensive herbicide which provides one component of many effective mixtures in corn, precludes planting any crop other than corn or sorghum in areas of the U.S. where precipitation is low and irrigation is required. There is substantial uncertainty on the effect of many soil residual herbicides on subsequently planted cover crops since most herbicide labels don't specify plant-back recommendations to common cover crop species. Due to these crop rotation restrictions, adopting low-cost, effective SOA mixtures in these areas may actually reduce adoption of other resistance management practices such as crop rotation and cover crops.

Although there is compelling data to suggest that herbicide mixtures could delay resistance evolution, herbicide mixtures increase the cost of weed control, and are sometimes incompatible with other best management practices. Too much focus on implementing herbicide mixtures may actually inhibit adoption of herbicide resistance management practices. Effective SOA mixtures are a tool that should be implemented where possible, but herbicide resistance is a problem that is unlikely to be solved through the use of more herbicides. Since the effectiveness of herbicide mixtures is well-understood, it is important for weed science researchers to integrate concepts of non-herbicide control strategies as they evaluate management strategies for herbicide-resistant weeds.

Author's contributions

All authors read and agreed to the final version of the manuscript. ARK, EGM, NCL, and ATA conceived of the methodology for this study. NCL and ATA compiled efficacy and cost data. ARK wrote the optimization function, analyzed the data, and wrote the methods section. ATA wrote a majority of the first draft of the manuscript. ARK, EGM, NCL, and ATA wrote, reviewed, and edited the manuscript.

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Supplementary Table - Herbicide products selected by the optimization function for each scenario

Scenario	Effective weed control	Effective mixture	Active ingredients in mixture
Corn, Palmer amaranth, no resistance	glyphosate	glyphosate + atrazine	glyphosate + atrazine
Corn, Palmer amaranth, Group 5 resistance	glyphosate	glyphosate + Basis Blend	Glyphosate + rimsulfuron + thifensulfuron methyl
Corn, Palmer amaranth, Group 9 resistance	atrazine	atrazine + Basis Blend	atrazine + rimsulfuron + thifensulfuron methyl
Corn, Palmer amaranth, Group 5 & 9 resistance	Basis Blend	Basis Blend + Sharpen	rimsulfuron + thifensulfuron methyl + saflufenacil
Corn, Palmer amaranth, Group 5 & 14 resistance	glyphosate	glyphosate + Basis Blend	Glyphosate + rimsulfuron + thifensulfuron methyl
Corn, Palmer amaranth, Group 2 & 9 resistance	atrazine	atrazine + Sharpen	Atrazine + saflufenacil
Corn, Palmer amaranth, Group 2, 5, 9, & 14 resistance	Armezon	Armezon + Parallel Plus	Topramezone + atrazine + metolachlor
Corn, kochia, no resistance	glyphosate	glyphosate + atrazine	glyphosate + atrazine
Corn, Palmer amaranth & kochia, no resistance	glyphosate	glyphosate + atrazine	glyphosate + atrazine
Corn, Palmer amaranth & kochia, Group 9 resistance	atrazine	atrazine + Basis Blend + Solstice	atrazine + rimsulfuron + thifensulfuron methyl + fluthiacet-methyl + mesotrione
Corn, Palmer amaranth & kochia, Group 5 resistance	glyphosate	glyphosate + Basis Blend + Solstice	Glyphosate + rimsulfuron + thifensulfuron methyl + fluthiacet-methyl + mesotrione
Corn, Palmer amaranth & kochia, Group 5 & 9 resistance	Basis Blend + Solstice	Basis Blend + Solstice + Starane Ultra + Sharpen	rimsulfuron + thifensulfuron methyl + fluthiacet-methyl + mesotrione + fluroxypyr + saflufenacil
Soybean, waterhemp, no resistance	Authority First	Authority First + glyphosate	sulfentrazone + cloransulam-methyl + glyphosate
Soybean, waterhemp, Group 2 resistance	Authority First	Authority First + glyphosate	sulfentrazone + cloransulam-methyl + glyphosate
Soybean, waterhemp, Group 9 resistance	Authority First	Authority First + Syn-chrony XP	sulfentrazone + cloransulam-methyl + chlorimuron-ethyl + thifensulfuron methyl
Soybean, waterhemp, Group 14 resistance	glyphosate	glyphosate + Syn-chrony XP	glyphosate + chlorimuron-ethyl + thifensulfuron methyl
Soybean, waterhemp, Group 2 & 14 resistance	glyphosate	glyphosate + Vise	glyphosate + fomesafen + metolachlor
Soybean, waterhemp, Group 2 & 9 resistance	Authority First	Authority First + Vise	sulfentrazone + cloransulam-methyl + fomesafen + metolachlor
Soybean, waterhemp, Group 2, 9, & 14 resistance	Vise	Vise + Enlist Duo	fomesafen + metolachlor + 2,4-D + glyphosate
Soybean, kochia, no resistance	Authority First	Authority First + glyphosate	sulfentrazone + cloransulam-methyl + glyphosate
Soybean, waterhemp & kochia, no resistance	Authority First	Authority First + glyphosate	sulfentrazone + cloransulam-methyl + glyphosate
Soybean, waterhemp & kochia, Group 9 resistance	Authority First	Authority First + metribuzin + Synchro-ny XP	sulfentrazone + cloransulam-methyl + metribuzin + chlorimuron-ethyl + thifensulfuron-methyl
Soybean, waterhemp & kochia, Group 14 resistance	glyphosate	glyphosate + metribuzin + Synchro-ny XP	glyphosate + metribuzin + chlorimur-on-ethyl + thifensulfuron-methyl
Soybean, waterhemp & kochia, Group 2 resistance	Authority First	Authority First + glyphosate	sulfentrazone + cloransulam-methyl + glyphosate
Soybean, waterhemp & kochia, Group 2 & 9 resistance	Authority First	Authority First + metribuzin + Vise	sulfentrazone + cloransulam-methyl + metribuzin+ fomesafen + metolachlor
Soybean, waterhemp & kochia, Group 2, 9, & 14 resistance	Metribuzin + Vise	Authority Elite + Trivence	s-metolachlor + sulfentrazone + chlorimuron ethyl + flumioxazin + metribuzin

Continue

Continuation

Dry bean, Palmer amaranth, no resistance	Reflex	Reflex + Pursuit	fomesafen + imazethapyr
Dry bean, Palmer amaranth, Group 2 resistance	Reflex	Reflex + Outlook	fomesafen + dimethenamid-P
Dry bean, Palmer amaranth, Group 14 resistance	Pursuit	Pursuit + Outlook	imazethapyr + dimethenamid-P
Dry bean, Palmer amaranth, Group 2 & 14 resistance	Prowl H2O	Prowl H2O + Outlook	pendimethalin + dimethenamid-P
Dry bean, Palmer amaranth & kochia, no resistance	Reflex	Reflex + Pursuit	fomesafen + imazethapyr
Dry bean, Palmer amaranth & kochia, Group 2 resistance	Reflex	Reflex + Basagran + Outlook	fomesafen + bentazon+ dimethenamid-P
Dry bean, Palmer amaranth & kochia, Group 14 resistance	Pursuit	Pursuit + Basagran + Outlook	imazethapyr + bentazon+ dimethenamid-P
Dry bean, Palmer amaranth & kochia, Group 2 & 14 resistance	Prowl H2O	Prowl H2O + Basagran + Outlook	pendimethalin + bentazon+ dimethenamid-P

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