Weed Science

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Occurrence and management of herbicide resistance in annual vegetable production systems in North America

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Review

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Abstract

Herbicide resistance has been studied extensively in agronomic crops across North America but is rarely examined in vegetables. It is widely assumed that the limited number of registered herbicides combined with the adoption of diverse weed management strategies in most vegetable crops effectively inhibits the development of resistance. It is difficult to determine whether resistance is truly less common in vegetable crops or whether the lack of reported cases is due to the lack of resources focused on detection. This review highlights incidences of resistance that are thought to have arisen within vegetable crops. It also includes situations in which herbicide-resistant weeds were likely selected for within agronomic crops but became a problem when vegetables were grown in sequence or in adjacent fields. Occurrence of herbicide resistance can have severe consequences for vegetable growers, and resistance management plans should be adopted to limit selection pressure. This review also highlights resistance management techniques that should slow the development and spread of herbicide resistance in vegetable crops.

Introduction

Vegetable crops account for a large proportion of total farm gate value in the United States and Canada. In 2020, there were 942,900 ha of vegetables and melons harvested in the United States with the utilized production valued at US$13.1 billion (USDA-NASS 2020). Sweet corn (*Zea mays* L.), tomatoes (*Solanum lycopersicum* L.), and snap beans (*Phaseolus vulgaris* L.) were the top three vegetables in terms of harvested area with a combined utilized value of US$2.67 billion. In Canada, vegetable production represents a total farm gate value of Can$1.3 billion, with more than 88% of the vegetable-producing area located within two provinces: Ontario and Quebec (Agriculture and Agi-Food Canada 2020). Processing field tomatoes, carrots (*Daucus carota* L. var. *sativus* Hoffm.), and dry bulb onions (*Allium cepa* L.) represented the highest production in terms of farm gate value, with values of Can $109 million, Can$133 million, and Can$110 million, respectively.

Weeds can significantly affect crop yield and quality. Over the past few decades, growers have increasingly relied on chemical control options to suppress unwanted vegetation in most crops due to ease of use, effectiveness, and relatively low cost compared with other management options. Physical weed control, including hand weeding, was the dominant mechanism for eliminating unwanted vegetation in crops until the introduction of synthetic herbicides (McErlich and Boydston 2014; Oerke 2006). Herbicides are now widely regarded as the most effective weed control method, killing up to 99% of difficult-to-control weeds in some situations (Foster et al. 1993). The use of nonchemical weed control tactics continues to decline due to associated limitations such as labor intensity and high costs.

Herbicides have been widely adopted globally as an effective and economic tool for growers. The widespread use of synthetic herbicides has facilitated the evolution of herbicide-resistant weeds, especially in agronomic crops (Gaines et al. 2020; Radosevich and Holt 1984). Currently, there are 505 unique cases (species by site of action [SOA]) of herbicide-resistant weeds (153 dicots and 111 monocots) worldwide (Heap 2021). According to Heap (2021), weeds have evolved resistance to 164 herbicides and 21 of 31 SOAs. Herbicide-resistant weeds infesting cotton (*Gossypium hirsutum* L.), cereals, corn, and soybean [*Glycine max* L. (Merr.)] in the United States currently account for 64, 101, 181, and 226 confirmed cases, respectively, and pose a serious threat to farm sustainability (Heap 2014).

There are far fewer herbicides used or registered for use within vegetables compared with agronomic crops, leaving growers with access to fewer unique SOAs (Bell et al. 2000). This disparity is due in part to the high crop value of most vegetable crops, smaller acreage on which vegetable crops are typically grown, increased sensitivity to available herbicides, and manufacturer's fear of potential crop injury and liability (Fennimore and Doohan 2008; Kunkel et al. 2008). Despite this limitation, herbicides have been broadly adopted. For example, surveys conducted by the U.S. Department of Agriculture–National Agricultural Statistics Service on select crops found that herbicides are applied on 44%, 92%, 76%, and 51% of the planted acres for bell peppers (*Capsicum annuum* L.), onions, pumpkins (*Cucurbita pepo* L.), and squash (*Cucurbita* spp.), respectively (USDA 2017). While federal programs (Interregional Research Project No. 4 within the United States and the Pest Management Center in Canada) have facilitated the approval of herbicide technologies for specialty crops, the lack of registered SOAs in many vegetables is an ongoing issue. This scarcity and the subsequent shortage of tank-mix options may inadvertently result in an increased selection pressure for herbicide-resistance development (Beckie and Reboud 2009).

Herbicide resistance has historically been less of an issue in vegetables compared with agronomic crops, but it does occur. As of 2021, there have been 21 resistant weed species identified in vegetable production systems (Heap 2021). There are many potential explanations for the lower incidence of herbicide resistance in vegetables. For example, one could argue that the lack of resistance can be explained by the fact that many SOAs have been used for a much shorter time frame in vegetable crops versus agronomic crops or that harvested vegetable acreage only accounts for less than 1 million ha of land compared with many millions of hectares of agronomic crop production within the United States (USDA-NASS 2020). It is therefore likely that reduced resistance incidence can be partially attributed to reduced overall population exposure and shorter temporal exposure duration within vegetable fields. However, this assumes that there is no overlap in agronomic and vegetable crop production, with the two categories occurring within a separate land base. Of course, this is not true in many regions, and as a result, resistant weeds that initially occur in agronomic crops can also become a serious issue within vegetable crops. In almost every case, herbicides registered in vegetables were initially registered for use in agronomic production, and when the two crop categories are rotated on the same land base, the result is often utilization of the same SOAs in crops.

Reduced resistance incidence is undoubtedly also associated with the wide-scale adoption of integrated weed management (IWM) programs by vegetable growers. Vegetable crops tend to be poor competitors with weeds, and this, combined with limited herbicide options, has led to the adoption of diverse weed management programs and increased management intensity. Management options may include fumigation, mulches, tillage, herbicides, and hand weeding as part of a robust, holistic approach to weed management (Pannacci et al. 2017; Stevens et al. 2016; Vencill et al. 2012; Yu et al. 2018). Each of these management options can be effective on its own, but when implemented in an IWM program, these options offer a degree of resistance management sustainability (Fennimore et al. 2014). Other cultural practices common to vegetables, such as planting crops during different times of the season to avoid the same weed emergence patterns and use of irrigation for rapid crop development and herbicide activation, are also beneficial in mitigating herbicide-resistance development (Fennimore et al. 2014; Pannacci et al. 2017; Vencill et al. 2012). Highly diverse crop rotations are used in some regions, often driven by disease and nematode pressure, and further lessen the potential for herbicide resistance. Crop rotations also limit the use of long-lasting residual herbicides while increasing the use of different herbicide SOAs with shorter residual activity (Collange et al. 2014; Subbarao et al. 2007; Vencill et al. 2012).

Unfortunately, IWM programs have been simplified over time in some regions, with growers increasingly reliant on fewer management options. For example, crop rotations have been simplified or even eliminated in some cases, while reliance on herbicides has increased. Repeated use of the same SOAs was historically quite rare in vegetables, and even when it occurred, intensive crop rotations ensured that different chemistries were frequently rotated (Gast 2008; Kunkel et al. 2008). This is no longer true in many vegetable-cropping systems. The loss of methyl bromide and the subsequent adoption of fumigants that tend to provide inconsistent weed control (Wu et al. 2019; Yu et al. 2021a) led to increased reliance on preemergence herbicides (Gilreath and Santos 2005; Gilreath et al. 2006; Yu et al. 2019a). This is especially important in regions where crop rotation occurs less frequently due to: (1) high infrastructure costs, (2) high land prices, (3) the need to base crop selection on crop demand, and (4) rapid urban expansion (Dukes et al. 2010; Fedoroff et al. 2010; Richards and Rickard 2020). In many areas of Florida, for example, the same vegetable crop is grown every year on the same land, and in some cases, this has occurred for decades (NSB, personal observation). The inability to rotate crops, heavy reliance on limited herbicide options, and reduced hand weeding due to cost and availability of labor, all suggest that herbicide resistance is likely to become a serious issue in vegetable crops. This is even more likely to occur when vegetable crops are grown on land where agronomic crops were grown in the past.

It is also important to note that there are far fewer weed scientists who conduct research on vegetable crops than on agronomic crops, and consequently there are fewer people looking for incidence of resistance. Based on a survey conducted in 2009, within the northeastern United States, there were approximately 75 faculty full-time equivalent positions (FTE) focused on weed management in agronomic/range crops versus 17 FTE's focused on vegetables (Derr and Rana 2011). The breakdown for other regions is unknown, but similar trends are expected. The lack of focus on resistance has been highlighted as an issue of concern (Fennimore and Doohan 2008), and the issue is further compounded by the lack of funding for resistance management research in vegetables compared with agronomic crops.

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Herbicide Resistance

According to the Weed Science Society of America (WSSA), herbicide resistance is defined as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type. In a plant, resistance may be naturally occurring or induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis" (https://wssa.net/wssa/weed/resistance/herbicide-resistance-and-herbicide-tolerance-definitions/). Herbicide resistance within a weed population occurs as a consequence of selection pressure imposed by the continuous use of the SOA (Jasieniuk et al. 1996). Genetic mutations naturally occur in a weed population, and selection occurs for mutations that facilitate survival. Mutations can also make a plant resistant to a herbicide that was previously effective. The larger the population, the higher the chance for resistance development, because the risk increases with every additional plant exposed to the selective pressure imparted by a herbicide (Diggle et al. 2003). Once resistant biotypes become established, additional applications will only kill the susceptible weeds, allowing resistant survivors to grow and reproduce with fewer competitors. Currently, 262 weed species (152 dicots and 110 monocots) have evolved resistance to 23 of the 26 known herbicide SOAs and to 167 different herbicides worldwide (Heap 2021).

Herbicides inhibit specific sites or enzymes within a plant (i.e., target sites), and interactions with the SOA can culminate in plant death. Herbicides are grouped according to their mechanism of action (MOA), which describes how a herbicide acts in a weed at a target site at a molecular level. Resistant weeds can survive herbicide application through a variety of mechanisms (Beckie and Tardif 2012; Powles and Yu 2010) that can be generally divided into two broad categories: target-site resistance and non–target site resistance mechanisms. Target-site resistance mechanisms include structural changes to the target binding site (often within an enzyme), preventing or reducing a herbicide's ability to bind to the target site (Heap 2014). Non–target site resistance describes mechanisms that are not directly associated with changes to the herbicide-specific target site; for example, alterations in the plants' cuticular layers altered herbicide uptake and translocation to the target site, enhanced herbicide metabolism in weeds, and enhanced neutralization of cytotoxic molecules generated by the herbicide MOA (Délye et al. 2011).

Occurrence of Herbicide Resistance in Vegetable Crops

In the following sections we will: (1) highlight the frequency of herbicide resistance within vegetable crops within specific regions of the USA and Canada, (2) summarize reports of herbicide resistance in vegetable crops, (3) highlight incidences where resistance is likely to have arisen within vegetable crops, and (4) provide general resistance management recommendations for vegetable crops. In many regions, vegetable crop production occurs in fields where agronomic crops are grown or in adjacent fields. In these situations, it is likely that herbicide-resistant weeds common in agronomic crops will occur and cause problems in vegetable crops. A few such instances are also documented in this paper.

Southeast

A wide variety of vegetable crops are grown across the southeastern United States, often near cotton, peanuts (*Arachis hypogaea* L.), corn, and soybean crops. Florida is the largest producer of vegetable crops within the region but lacks the large hectarage of agronomic crops typical of other regions. It can be difficult to trace the origin of resistance, but several cases in Florida present scenarios where it is very possible that resistance may have originated within the vegetable crop itself, rather than in a rotation partner.

A resistant biotype of goosegrass [*Eleusine indica* (L.) Gaertn.] that demonstrated a 30-fold increase in resistance to paraquat was found in Manatee County (Buker et al. 2002). This species is widespread in vegetable crops, and paraquat is frequently used in row middles for weed control as well as crop termination, and it is possible that resistance originated within the tomato fields where it was first documented (Heap 2021). Paraquat-resistant *E. indica* has also been documented in tomatoes in Alabama (McElroy et al. 2021), so the origin of the resistant biotypes cannot be determined with certainty. The presence of the resistant biotypes in two regions suggests movement of seeds or that the occurrence of the resistant biotype is widespread (Heap 2021). Given both the unknown origin and occurrence in two nearby states, surveillance of tomato and similar horticultural fields within Florida, Georgia, and Alabama is advisable.

Two paraquat-resistant populations of American black nightshade (*Solanum americanum* Mill.) were found in Florida tomato fields, one in Collier County demonstrating a 12-fold increase in tolerance and one in Manatee County demonstrating an 8-fold increase in tolerance compared with a sensitive biotype (Bewick et al. 1990). Group 9 (5-enolpyruvylshikimate-3-phosphate synthase inhibitors) resistance to glyphosate was also documented in ragweed parthenium (*Parthenium hysterophorus* L.) in fallow fields in southern Florida where glyphosate is regularly used for fallow management (Fernandez et al. 2015). These examples provide evidence that resistance has arisen within vegetable crops, and it is possible that other resistant weed species exist but have not yet been identified.

In the remaining southeastern states, herbicide resistance has frequently arisen within agronomic crops such as cotton, peanuts, and soybeans. Many vegetable crops are grown in rotation with agronomic crops, and as a result, herbicide-resistant weeds can be a problematic. For example, sweetpotato [*Ipomoea batatas* (L.) Lam.] is an important crop in South Carolina that has the potential to be negatively impacted by Palmer amaranth (*Amaranthus palmeri* S. Watson) resistance to inhibitors of protoporphyrinogen oxidase (PPO). *Amaranthus palmeri* is one of the most common and troublesome weed species in agronomic crops such as cotton throughout the Southeast, with resistance to several SOAs (Salas et al. 2016). The largest sweetpotato growers either rotate with cotton or have cotton fields near their sweetpotato production. Because flumioxazin and now fomesafen are the primary residual herbicides used to control *Amaranthus* species in sweetpotato, PPO inhibitor–resistant *A. palmeri* is a concern. *S*-metolachlor can be applied 2 wk after transplanting, but any *A. palmeri* that emerge after transplanting and before application will not be controlled by *S*-metolachlor.

In states like Florida and South Carolina, there have been multiple unconfirmed reports of reduced halosulfuron efficacy on *Cyperus* species in watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] and tomato. This is a significant concern, because we know resistance to acetolactate synthase (ALS) inhibitors develops rapidly (Heap 2021) and halosulfuron is the only registered in-crop management option for *Cyperus* in crops like tomato. There is the potential for reduced halosulfuron use, as stronger polymer mulches have been developed with improved

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tolerance to *Cyperus* spp. shoot penetration (Charter Next Generation-Plastics, Milton, WI, USA 53563), but these products are new and have not been widely adopted.

Northeast

Herbicide-resistant weeds occur in every state in the mid-Atlantic and northeastern United States, with most reports originating from agronomic systems including corn, soybean, and wheat (*Triticum aestivum* L.) (Heap 2021). With respect to vegetables, four unique resistance cases have been formally reported in the International Herbicide-Resistant Weed Database; these include ALS–inhibitor resistant livid amaranth (*Amaranthus blitum* L., 1993, New Jersey), smooth pigweed (*Amaranthus hybridus* L., 2000, Delaware), ALS– and photosystem II (PSII)–inhibitor resistant redroot pigweed (*Amaranthus retroflexus* L., 1998, Pennsylvania), and glyphosate-resistant *A. palmeri* (2019, Connecticut) (Heap 2021). Biotypes of *A. blitum* and *A. hybridus* with resistance to imazethapyr have also been reported in vegetables in both New Jersey and Delaware (Heap 2021; Whaley et al. 2006). Results from dose–response assays showed that the Delaware population exhibited 537-fold resistance to imazethapyr compared with a susceptible check (Whaley et al. 2006). The same population was found to be 80-fold resistant to pyrithiobac, 15-fold resistant to thifensulfuron, and 6- and 7-fold resistant to cloransulam and chlorimuron, respectively, compared with susceptible standards.

Amaranthus retroflexus with resistance to ALS inhibitors was first observed in Pennsylvania in 1998 (Heap 2021; Lingenfelter and Curran 2001). The original population was collected from a farm that grew corn, wheat, soybean, and forages, in addition to raising livestock. In 2004, a population of *A. retroflexus* collected from a mixed vegetable and grain farm was found to be multiple herbicide resistant to ALS inhibitors and atrazine (Lingenfelter and Curran 2001).

Amaranthus palmeri resistant to glyphosate was reported in pumpkin in Connecticut in 2019 and currently infests about 160 ha in the state (Heap 2021). *Amaranthus palmeri* is the most troublesome weed in the United States and commonly infests vegetable-cropping systems in Delaware, Maryland, and Virginia. In Virginia, anecdotal observation suggests that glyphosate-resistant *A. palmeri* and *A. hybridus* are common issues in vegetable crops like pumpkins, tomato, and potato (*Solanum tuberosum* L.) (VS, personal observation). These herbicide-resistant weeds also pose challenges in other vegetable crops such as leafy vegetables, cole crops, spinach (*Spinacia oleracea* L.), asparagus (*Asparagus officinalis* L.), and peas (*Pisum sativum* L.). Although *A. palmeri* is not a widespread problem in other northeastern vegetable systems, this amaranth species is becoming a concern in asparagus in New Jersey (TB, personal observation) and other neighboring states. *Amaranthus palmeri* was recently identified in muck soil production systems, which include soybean in rotation with vegetables, in southeastern New York. Herbicide-resistance screening assays are currently ongoing, but preliminary assays suggest that the population is resistant to glyphosate and several ALS-inhibiting chemistries.

Resistance to linuron in Powell amaranth (*Amaranthus powellii* S. Watson ssp. *powellii*) was confirmed in four populations collected from carrot fields in central New York (LMS, personal observation). A resistant *A. powellii* population survived 1,680 to 3,360 g ha^{-1} of linuron, whereas a susceptible population was completely controlled at 420 g ai ha^{-1} (LMS, unpublished data). Profiling of herbicide-resistant weeds in many parts of the northeastern region is ongoing, but additional resources are needed.

Central

The central region consists of 19 states forming a rather large upside-down triangular area, with the northern boundary of states reaching from Montana to Ohio down to Texas and then back to Montana. All fields, regardless of the crop grown are generally dominated by two species that most influence the selection of specific weed management practices. The two dominant species that pose the greatest threat for resistance in vegetables, even though none have been reported, are waterhemp [*Amaranthus tuberculatus* (Moq) Sauer] and kochia [*Bassia scoparia* (L.) A.J. Scott]. What makes *A. tuberculatus* so dangerous is its biological characteristics, including rapid growth rate, C_4 growth habit, high seed production, asynchronous seed germination, and dioecy. All of these characteristics have contributed to weediness and widespread herbicide resistance (Busi and Powles 2009; Chatham et al. 2015; Costea et al. 2005; Tranel 2021; Tranel and Trucco 2009). Both species are likely to be an issue in vegetables grown in rotation with agronomic crops.

The International Herbicide-Resistant Weed Database records several weeds with Group 5 resistance in Michigan, including common purslane (*Portulaca oleracea* L.) in carrot; *A. powellii* and *A. retroflexus* in asparagus; ladysthumb (*Polygonum persicaria* L.; syn.: *Persicaria maculosa* Gray), eastern black nightshade (*Solanum ptychanthum* Dunal), common groundsel (*Senecio vulgaris* L.), and horseweed [*Conyza canadensis* (L.) Cronquist; syn.: *Erigeron canadensis* L.] in highbush blueberry (*Vaccinium corymbosum* L); and prostrate pigweed (*Amaranthus blitoides* S. *Watson*) in mint (*Mentha spicata* L.) (Heap 2021). Group 1–resistant large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and giant foxtail (*Setaria faberi* Herrm.) were discovered in a Wisconsin rotation of carrots, onions, and corn (Stoltenberg and Wiederholt 1995; Wierholt and Stoltenberg 1995).

Pacific Region

The western states are the largest vegetable producers in the United States, with a combined planted area of more than 640,000 ha in 2019, approximately 56% of the total U.S. cultivated area (USDA-NASS 2020). California is the largest producer, with 40% of the national vegetable acreage. In the western states, resistance was confirmed in 32 weed species and more than 79 unique cases (Heap 2021). Most of the reported cases were initially identified in crops other than annual vegetables.

With respect to vegetables, littleseed canarygrass (*Phalaris minor* Retz.) was confirmed to have evolved resistance to Group 1 herbicides in onion in California in 2001 (Heap 2021). Group 1 herbicides are important selective herbicides in vegetable crops, and resistance to Group 1 has already been reported in nearly all western states that produce vegetables. Resistance to the PSII inhibitors is also present in the western states. *Senecio vulgaris* resistant to Group 5 herbicides was reported in asparagus in California in 1981 (Heap 2021). In Oregon, resistance to Group 6 has been reported in bromoxynil-resistant *S. vulgaris* in mint and bentazon-resistant common lambsquarters (*Chenopodium album* L.) in snap beans (Riboldi et al. 2020). These crops can be grown in rotation with grass seed, in which resistance to the PSII inhibitors has also been documented.

Fifteen cases of resistance to Group 1 herbicides have been reported in the western United States, with some cases found in corn, wheat, and rice (*Oryza sativa* L.) systems. Additional cases of Group 1 resistance could have detrimental effects on vegetable production. Group 1 resistance in annual summer grasses like barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] would have a devastating effect on onion production in Oregon and Idaho (J Felix, Oregon State University, personal communication).

Resistance to Group 5, 6, and 7 herbicides was most extensively documented in mint and grass seeds. In Oregon, resistance to Group 6 is reported in bromoxynil-resistant *S. vulgaris* in mint and bentazon-resistant *C. album* in snap beans (Riboldi et al. 2020). Herbicides in the Groups 5, 6, and 7 are used to manage weed species resistant to Group 1 and 9 herbicides in vegetables. No resistance has been reported to PPO inhibitors, Group 14, in the western states. This is a herbicide SOA frequently used in vegetable crops. Although crop rotation is presented as an effective tool to reduce herbicide resistance, it can introduce problems when herbicides of similar MOA are used across multiple crops. This is evident in the Oregon Willamette Valley, where grass seed acreage is often rotated with vegetable production.

Canada

Herbicide resistance in Canadian vegetable-producing areas has been slower to develop when compared with field crops; however, there are several cases of herbicide resistance that have been identified and verified in Canada. For example, herbicide-resistant *D. sanguinalis* has been identified in carrots and onions (Heap 2021). Herbicide-resistant wild oats (*Avena fatua* L.), wild buckwheat [*Fallopia convolvulus* (L.) Á. Löve], *S. media*, *A. fatua*, and green foxtail [*Setaria viridis* (L.) P. Beauv.] have been reported in dry pea. Herbicide-resistant common ragweed (*Ambrosia artemisiifolia* L.), *A. retroflexus*, and *A powellii* have been identified in carrot (Heap 2021). Resistance is widespread within Ontario populations of pigweeds (*Amaranthus* spp.) due to multiple PSII mutations (Davis et al. 2019). An alarming trend in the Ontario and Quebec vegetable-growing regions is the recent discovery of weed populations that have resistance to multiple SOAs (RN, unpublished data).

Consequences of Herbicide Resistance in Vegetable Crops

The previous sections on herbicide resistance in different regions of North America demonstrate that herbicide resistance has likely arisen within vegetable crops and that vegetable crops are grown on land where resistance already occurs. It is likely true that herbicide resistance develops more slowly in vegetable crops than agronomic crops, but once resistance occurs, the negative impacts can be devastating. The situation is exacerbated by the limited number of herbicides registered for use in vegetable crops, which means (1) the use of tank mixes or herbicide rotation is not an option in many vegetable crops, leading to increased selection pressure; (2) once resistance occurs, there are no alternative herbicides; and (3) the loss of an SOA has a long-term effect, because the rate of registrations within vegetable crops is slow, with very few new SOAs.

The loss of a registered SOA forces growers to adopt alternative management options. While this sounds like a positive outcome, the reality is herbicides are used by vegetable crop growers because they are cheaper, require less labor, are more effective than many of the alternative tools, can be utilized across a broader range of environmental and field conditions, and have reduced environmental impact. For example, the ability to hand weed vegetable crops is often highlighted as an effective management option that makes resistance management a nonissue in vegetable crops. This is an overly simplistic view that overlooks the fact that hand weeding can cause crop damage, the practice is expensive, profit margins for many vegetable crops make this practice unrealistic, and labor shortages limit the availability of crews to manually remove weeds. Comparisons between organic and conventional field vegetable production estimated that hand weeding was the most expensive of all weed management techniques. For example, in strawberries [*Fragaria* × *ananassa* (Weston) Duchesne ex Rozier subsp. *ananassa*], tomato (*Solanum lycopersicum* L.), broccoli (*Brassica oleracea* L. var. *botrytis*), and lettuce, hand-weeding costs were estimated at US$809, $153, $103, and $89 ha^{-1}, respectively (Klonsky 2012). It is possible in the long-term that robotic weeders may facilitate mechanical removal of weeds without herbicides, but this technology has not been widely adopted to date and most mechanical weed removal technologies are only feasible if preemergence herbicides are used to reduce the emerging weed populations. Herbicides were broadly adopted in agronomic crops because they make economic and environmental sense. The same is true in vegetable crops, and the loss of any SOA results in higher production costs for growers whose profit margins are already thin.

Many vegetable crops are poor competitors with weeds or are grown such that a competitive canopy is rarely formed. Extensive research has demonstrated yield loss in vegetable crops due to weed competition. For example, yield of crops such as garlic (*Allium sativum* L.), okra [*Abelmoschus esculentus* (L.) Moench], carrot, green bean (*Phaseolus vulgaris* L.), cucumber (*Cucumis sativus* L.), cabbage (*Brassica oleracea* L.), and tomato was reduced by 89%, 62%, 39% to 50%, 41%, 43%, 35%, and 53% when competing with purple nutsedge (*Cyperus rotundus* L.) for the entire season (William and Warren 1975). *Cyperus* spp. populations in greenhouse studies have been shown to reduce pepper yield by 70% to 73% and tomato yield by 51% (Morales-Payan et al. 1997; Motis et al. 2003). Season-long interference of various weed species, including *Amaranthus* spp., *C. album*, *A. artemisiifolia*, and ivyleaf morningglory (*Ipomoea hederacea* Jacq.) caused a 35% reduction in the number of marketable watermelons (Vollmer et al. 2020). Marketable yield of bare-ground summer squash (*Cucurbita pepo* L.) and cucumber declined by 50% and 86%, respectively, with season-long competition of *A. hybridus*, *C. album*, *S. faberi*, and *D. sanguinalis* in comparison to a weed-free control (Besançon et al. 2020). Summer cabbage yields were reduced by 47% to 100% when competing with naturally occurring weed populations (Roberts et al. 1976). These data demonstrate that ineffective weed management due to the loss of effective SOAs or herbicide resistance could have devastating effects on vegetable yields. This is an especially critical issue in vegetables, where the potential for economic losses is very high due to high production costs compared with agronomic crops.

Weeds can also have significant effect on crop quality, which can have a direct effect on economic return. For example, cabbage shipments from Florida have been rejected when *C. album* seeds dropped into the forming head, causing discoloration (NSB, personal observation). Weeds can also have indirect negative effects by functioning as a host for pathogens (French-Monar et al. 2006), viruses (Goyal et al. 2012), nematodes (Rich et al. 2009), and insects (Palumbo 2013).

We conclude that the development of herbicide resistance has the potential to have a larger impact on management options, management choices, crop yields, and economic return in vegetable crops compared with agronomic crops. At the same time, we acknowledge that very little effort has been expended in most states to educate vegetable growers about the importance of resistance management. There is a need for herbicide-resistance management training and educational materials focused on the needs of vegetable growers. The following section provides a brief overview of some best management practices that could form the basis of strong IWM programs.

Recommended Best Management Practices for Vegetable Crops

Norsworthy et al. (2012) published a paper focused on best management practices (BMPs) to reduce the risk of herbicide resistance in agronomic crops. There are some similarities between agronomic and vegetable crop production methods, but as pointed out throughout our paper, there are also distinct differences. Consequently, we will focus on BMPs for herbicide resistance that are unique to vegetable crops or BMPs that are utilized in agronomic production but are modified for use in vegetable crops. The authors are aware that a separate paper could be written on each recommended BMP, and our goal is only to provide a summary of resistance management options that could be adopted. In every situation, resistance management will be most effective if multiple tools or approaches are integrated into an IWM program.

BMP 1: Scouting

Scouting is the foundation for field-specific IWM programs and the first defense against establishment of herbicide-resistant biotypes. A solid scouting program will monitor and record the presence, location, and abundance of weeds. Annual record keeping is critical, as it will help growers determine when control measures are inadequate. Within each field, scouting activities should focus on preventing the production of weed seeds or vegetative reproductive structures and identifying plants that survive herbicide applications for possible inclusion in resistance screening studies. Success requires scouting during the time interval when herbicides are expected to have killed plants but before weed seeds are typically produced. If possible, monitor changes in weed control and population dynamics over time. It is important to note that the importance of herbicide-resistance management within vegetable crops has historically been minimized and ignored. Consequently, crop scouts rarely consider resistance as an issue that should be monitored. Training for vegetable growers and scouts regarding the importance of this issue is needed.

BMP 2: Biological Information

A correct understanding of weed biology can lead to improved weed management. Even basic information, such as the season in which a weed emerges, its growth habit, and whether the plant is an annual or a perennial can help a grower determine which management options are likely to be effective and when they should be implemented. This is especially important for perennial weeds, as management timing in relation to the flow of nutrients in the plant can alter herbicide efficacy. It is also important to note when weeds need to be removed to minimize competitive interactions. Understanding when the critical weed-free period occurs for vegetable crops can have substantial impacts on yield and crop quality. Critical weed-free period estimates have been developed for many vegetables and provide growers with an important tool for determining when control measures should be implemented (Adkins et al. 2010; Chaudhari et al. 2016; Swanton et al. 2010).

Management timing is most effective when correlated with weed emergence as well as the developmental stage most susceptible to the management option selected. Weed emergence and developmental models facilitate predictions of when scouting and weed management measures need to be executed. Most of these models rely on measures of heat accumulation (growing degree days) to predict rates of emergence and development (White et al. 2012; Wu et al. 2013). For example, biological models were used to develop an IWM plan for black medic (*Medicago lupulina* L.) in strawberry using clopyralid. Efficacy declines when applications occur later in the season when *M. lupulina* is at later developmental stages (Sharpe et al. 2016, 2018a) and clopyralid translocation is limited (Sharpe 2017). Spray penetration through the strawberry canopy is also inhibited at later stages (Sharpe et al. 2018b). To address these issues, germination and emergence models can be used to predict when the plants will emerge (Sharpe and Boyd 2019a, 2019b), and developmental models can be used to determine when herbicides should be applied (Sharpe 2017). The success of this approach is an excellent example of how biological knowledge can play an integral role in an IWM program.

BMP 3: Plant into Weed-Free Fields

This is a critical step for most agronomic crops (Norsworthy et al. 2012). In vegetable crops, there tends to be significant tillage at the beginning of the season, especially where plasticulture or hilled production systems are adopted. This guarantees that fields are weed free at setup, and as such, BMP 3 may not be as critical for many vegetable crops. There are, however, instances when weed removal is extremely important before seeding or transplant, such as when: (1) weeds emerge between raised beds, (2) *Cyperus* spp. species puncture the plastic mulch, (3) minimum-till systems are used for vegetable crops, or (4) early-season planting in fields cultivated the previous fall prevents adequate tillage for weed removal.

BMP 4: Fumigants and Plastic Mulches

Plasticulture production systems are widely adopted by vegetable growers and typically consist of plastic-covered raised beds that may or may not be fumigated. The plastic mulches themselves provide a weed control barrier, with broadleaf and grass emergence limited to the space between the beds and plant holes punctured in the plastic mulch. *Cyperus* spp. are the only weeds that can puncture the mulch and compete with the crop. Fumigants are broad-spectrum pesticides that are typically injected into the raised bed as a liquid and transform into a gas that moves through the soil. Fumigants effectively control some weed species (Boyd et al. 2017; Freeman et al. 2017; Santos et al. 2006; Yu et al. 2019b), but weed control tends to be inconsistent, with inadequate control in many fields (Yu et al. 2020). In most cases, an application of one or more herbicides applied in conjunction with fumigants improves control compared with fumigation alone. For example, Gilreath and Santos (2004) reported that a 1,3-D:Pic mix combined with the herbicide napropamide decreased *C. rotundus* densities by

93% compared with fumigants applied alone. Season-long control of weeds typically improves with combination of fumigants, preemergence herbicides, and postemergence herbicides (Yu et al. 2020). However, all three options are only available for a limited number of vegetable crops, with no postemergence herbicides registered in many vegetable crops. It is important to note that the loss of the fumigant methyl bromide resulted in increased dependance on herbicides in many crops. This is further exacerbated by increased regulations associated with fumigant use in many regions across the country. The transition away from fumigation may be beneficial in some respects, but increased reliance on a limited number of herbicides could lead to increased incidence of resistance.

BMP 5: Optimal Herbicide Rate and Application Timing

In many vegetable production systems, herbicides are the primary method used for weed control. Companies that develop, manufacture, and sell these herbicides thoroughly test a product to determine its lowest effective use rates before product launch to ensure consistent performance and maximized value per dollar invested to growers (Copping 2002). While the need to follow label recommendations is paramount, numerous studies have examined the use of reduced herbicide rates. Most of this research was conducted with agronomic crops within an IWM system where practices that increase crop competitiveness are incorporated. For example, Nadeem et al. (2018) showed that by reducing corn row space and proper adjuvant selection, one could decrease herbicide cost and environmental damage by reducing the herbicide application rate. Zhang et al. (2000) examined previously published research on below labeled rate herbicide applications in corn, soybean, and wheat production over large geographic and temporal scales and concluded that using herbicides at below labeled rates was more successful when weed pressure was low, when done in conjunction with interrow cultivation, and when corn was grown rather than soybean or wheat. We conclude that the use of reduced rates is unlikely to be successful in vegetables in many situations, as planting density and patterns are often limited by the need to move equipment and people in the field, cultivation may not be an option in some management systems such as plasticulture production, and vegetables are known to be poor competitors.

There are situations where reduced rates may be a viable option. Sankula et al. (2001) reported that row spacing, herbicide rate, and herbicide application method had no effect on lima bean (*Phaseolus lunatus* L.) biomass or yield. Weed control was consistently improved with wide-row planting, even when reduced herbicide rates were used, which the authors attributed to cultivation that was used with wide-row planting. Yousefi and Rahimi (2014) reported that reduced rates of soil-applied herbicides in fennel (*Foeniculum vulgare* Mill.) followed by hand weeding provided similar season-long weed control and fennel seed yield as the labeled rates followed by hand weeding. Lahmod and Alsaadawi (2014) showed that adding a sorghum [*Sorghum bicolor* (L.) Moench] residue as a mulch improved weed control when herbicide rates were reduced up to 50% of the labeled rate and compared with identical herbicide rates without the sorghum residue mulch. They concluded that the integration of sorghum residues with reduced herbicide rates increased weed control as well as the soil physicochemical and physical soil properties. Similarly, Malik et al. (2008) reported that sweet corn in wild radish (*Raphanus raphanistrum* L.) or cereal rye (*Secale cereale* L.) cover crop plots without the half or full rate of atrazine and *S*-metolachlor produced less marketable yields. They concluded that this indicated that the combination of cover crops and herbicides was required to optimize yields and to obtain desirable weed control. Reduced herbicide rates were even used to decrease the competitiveness of a living mulch in fresh market tomatoes (Bhaskar et al. 2020). These authors reported that the reduced-rate herbicide and living mulch reduced weed biomass by up to 97% compared with the weedy check and increased the tomato yield by 51% to 71% compared with tomato in the living mulch–only treatment.

The use of reduced herbicide rates in vegetables is typically only successful when integrated with an IWM approach. Loken and Hatterman-Valenti (2010), when applying multiple reduced-rate postemergence herbicides for early-season weed control in onion, utilized additional herbicide applications to provide satisfactory season-long weed control. Dirksmeyer (2012) surveyed 134 carrot, leek (*Allium ampeloprasum* L.), and onion growers from Denmark, Germany, and the Netherlands, and reported that a combined chemical–mechanical weed control method using reduced herbicide rates was more efficient than the application of the herbicides at full rates or nonchemical weeding.

BMP 6: Herbicide Mixtures

Mixtures and rotation of herbicides with different MOAs are common resistance management recommendations (Norsworthy et al. 2012), and often the primary proactive and reactive tool to manage resistance. There is evidence that herbicide mixtures are a better management approach than rotations, as the probability of a mutation conferring resistance to two MOAs is low (Beckie et al. 2021). Mixtures may delay the selection of resistant biotypes (Diggle et al. 2003), and when used at high rates, additional MOAs help further delay selection (Lagator et al. 2013). The success of herbicide mixtures is predicated on overlapping weed control spectra, similar soil persistency, different MOAs, and lack of cross-resistance (Wrubel and Gressel 1994). Benefits of mixtures may include synergistic effects that help expand the weed control spectrum or reduce the frequency of herbicide use (Sukhoverkov and Mylne 2021). In some cases, plants resistant to individual MOAs may be controlled by mixtures (Busi and Beckie 2021).

Mixtures of herbicides have disadvantages as well. Herbicide mixtures may have a higher cost than using a different herbicide MOA. Thus, herbicide rotations may be a preferred alternative for some growers (Beckie and Reboud 2009). Mixtures are more commonly used when resistance to one of the MOAs is already present, and in that case, not all mixtures would meet the necessary conditions to be used as an effective resistance management tool (Jacquemin et al. 2009). Under this scenario, repeated use of a herbicide mixture would select for individuals that can cope with both herbicide MOAs, making this mixture ineffective; hence commercial premixes of herbicides may not always be the best alternative (Jacquemin et al. 2009). A single active ingredient formulation may give the flexibility needed for a site-specific recommendation.

BMP 7: Cultural Practices

Cultural weed management strategies form an important part of any IWM system, particularly in horticultural crops. Cultural weed management includes the use of such tools as crop rotation, cover crops, row spacing, and competitive crop cultivars. The following is a summary of potential tools for use in vegetable crops that can be effective resistance management options.

Crop Competition

Most vegetable crops are poor competitors with weeds, or they are grown in a manner that prevents them from forming a solid, competitive canopy. The need to move equipment and people through the field throughout the season combined with poor crop competitive ability makes it difficult to utilize vegetable crop canopies for weed control as is often done in agronomic crops. There are exceptions, of course; vegetable canopies can be used to suppress weeds, and this suppressive ability can be enhanced with variety selection and planting density (Colquhoun et al. 2017; Harrison and Jackson 2011; William and Chiang 1980; William and Warren 1975). However, plant spacing in most vegetable crops is selected based on management recommendations not associated with weed control, and cultivars are almost always selected based on disease resistance, yield, novelty, taste, appearance, or shelf-life. This is an area that may be of increasing importance when MOAs are limiting or resistance is a serious issue. Further research on planting patterns as well as cultivar selection for competitive ability may be desirable for some vegetable systems.

Crop Rotation

It has been established for decades that crop rotation influences weed populations, and this effect can be positive or negative (Blackshaw et al. 2001; Jordan et al. 1995; Koocheki et al. 2009; Norsworthy et al. 2012). It is not our goal to thoroughly review the effects of crop rotation but rather to identify it as a potential management tool. In many regions within the United States, vegetable crops are rotated with agronomic crops, and as previously noted, it is likely that herbicide-resistant weeds may occur within the vegetable crop. This can increase weed management costs in the vegetable component of the rotation but can also help reduce resistant weed populations for subsequent crops. The converse can also be true, with reduced weeds occurring in vegetable crops when rotated with competitive agronomic crops. In states like California and Florida, crop rotation is not a common practice due to high land and infrastructure costs associated with vegetable production. In Florida, there are fields where the same crop has been grown on the same fields for decades. As a result, selection pressure for resistance is likely high. However, even in these regions, properly implemented fallow programs when the same crop is grown annually can have a significant effect on weed populations. In fact, the management option selected for the fallow period may have a direct effect on weed densities within the crop, although not in every situation (Alves et al. 2013; Han et al. 2021; Yu et al. 2021a, 2021b). The use of herbicides within a fallow program also provides opportunities to rotate MOAs not registered within the crop itself. It seems reasonable to conclude that although the risk for the development of resistant weeds within a specialty crop is higher in regions where rotation is not a common practice, the potential for a wider range of resistant weeds causing a problem is even greater in regions where rotation with agronomic crops is common practice.

Living Mulches

Living mulches can be utilized in a variety of ways to suppress weeds in vegetable crops. For example, Brainard et al. (2004) examined the effect of overseeded hairy vetch (*Vicia villosa* Roth.), lana vetch [*Vicia villosa* Roth subsp. *varia* (Host) Corb.], or oat (*Avena sativa* L.) with or without weed control with a flex tine weeder and an S-tine cultivator. Cabbage yield was reduced when cover crops were interseeded at 10 d after transplant (DAT) but either vetch species could be sown 20 or 30 DAT without reducing cabbage yield. Weed control and cabbage yield were not different in the interseeded treatments than in those treatments that were cultivated in the absence of the living mulch. This would indicate that living mulches such as hairy vetch can be used for weed suppression in cabbage grown in rotation with other high-value vegetable crops, such as tomato. Sainju et al. (2001) estimated similar fruit yield, biomass, and nitrogen uptake in tomato grown after a fall cover crop of hairy vetch compared with tomato grown on bare ground and fertilized with 180 kg N ha^{-1}. In addition to replacing fertilizer requirements, hairy vetch mulch suppressed many annual weeds such as *C. album* that have developed resistance to the Group 2 and 5 herbicides (Sainju and Singh 1997). The potential for improving soil fertility and structure may justify the extra cost and management associated with interseeding living mulches in high-value production systems.

Cover Crops

In northern regions, the inclusion of competitive cereal crops such as barley (*Hordeum vulgare* L.)in rotation with vegetable crops such as carrot has been shown to reduce weed populations and increase crop yields in some instances. Leroux et al. (1996) showed that seedling recruitment and biomass of *C. canadensis* were decreased most when barley preceded a carrot crop. The reduced competition corresponded to a 35% to 50% increase in carrot yield. Biomass of *A. hybridus*, *C. album*, and hairy galinsoga (*Galinsoga quadriradiata* Cav.) was shown to be reduced 64% to 80% before cabbage transplanting the year after cover cropping with sorghum sudangrass (*Sorghum* × *drummondi*) compared with sunn hemp (*Crotalaria juncea* L.). Long-term suppression of some broadleaf weeds was attributed to sorghum sudangrass allelopathic activity (Besançon et al. 2021). Research has also shown that incorporating a regularly mowed legume cover crop in rotation with cabbage can be a more effective means of managing future weed and other pest populations than a grass cover crop. Bellinder (2004) showed that 2 yr of frequently mowed alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.) grown before cabbage had a similar effect on weed seedbank density as tillage and a herbicide treatment in sweet corn grown before cabbage. The allelopathic and competitive effects that grass cover crops, such as cereal rye, have on weed seedbanks (Weston 1996) may not be as great as that of mowed alfalfa or red clover. Frequent mowing of legume cover crops may reduce flowering and seed set of weeds, as well as increase cover crop competition with weeds for available resources. In the absence of tillage, this would concentrate weed seeds on the soil surface, which increases risk of decay and predation compared with seed buried by tillage (Liebman and Davis 2000). The ability of rotational and cover crops to reduce seed production and survival would have a significant impact on limiting the spread of herbicide-resistant species such as *C. canadensis*.

Extensive research has shown that weed growth and seed production can be reduced within a cover crop during the fallow period, and this may reduce weed problems and their associated management costs in a subsequent cash crop (Boyd et al. 2006). This only holds true if the weeds emerge during both time periods when the cover crop and the cash crop are growing. Poorly controlled weeds during the fallow period can lead to increased weed density in the cash crop, and crop volunteers and persistent weeds can function as hosts for crop pathogens and parasitic nematodes. In situations where there is persistent weed pressure and growers have limited weed management options in the cash crop, it should be feasible to implement weed control measures within the cover crop. For example, Boyd et al. (2006) evaluated the rotary hoe for weed management in cover crops and found that its use substantially reduced weed biomass and weed seed production. However, weed management efforts during the fallow period do not always lead to fewer weeds in the cash crop (Anonymous 2017; Sharpe et al. 2021; Yu et al. 2021a).

Fallow Management Programs

The summer conditions in some regions like Florida discourage summer vegetable and strawberry production due to high temperatures. Fields are often left fallow. Similarly, in the Great Plains region, annual cereal crops (e.g., winter wheat) are grown and rotated with fallow periods. These fallow periods can result in high weed populations if not managed properly and on time. In plasticulture production systems, weed populations during fallow periods are usually managed by the application of nonselective herbicides, cultivation, and cover crops. Aggressive management, such as glyphosate application, can help remove or reduce weeds. However, various studies have reported that excessive and repeated use of broad-spectrum herbicides often results in herbicide tolerance or resistance in weed populations (Peterson et al. 2018). Fallow periods do offer the opportunity to utilize SOAs that cannot be applied within the crop, which is a form of rotation of SOAs. This is an effective resistance management option when the same weed species emerge in both seasons.

A variety of fallow management options can reduce overall weed densities, including tillage, herbicides, and cover crops. Fallow tillage was reported to be effective in controlling yellow nutsedge (*Cyperus esculentus* L.) either alone or with summer solarization in the southeastern coastal areas (Johnson et al. 2007). Cover crops can effectively reduce weed density when utilized during a fallow period, as noted previously. In plasticulture strawberry or vegetable production, relay-cropping or double-cropping facilitates having plastic mulch in place for a longer period, resulting in a smaller fallow period, which ultimately inhibits weed germination and could disrupt the life cycle of some species (Yu et al. 2018).

BMP 8: Mechanical Weed Control

Vegetable production generally requires intensive tillage before, during, and after crop production. Plowing, disking, or harrowing are widely used during fallow periods before planting for weed removal and field preparation. No-till or conservation-tillage systems have been evaluated for vegetable crops but have not been widely adopted (Morse 1999). As a result, many of the resistance issues associated with no-till agronomic crops have not occurred in vegetables. Tillage effectively removes weeds that are present but also affects the vertical distribution of seeds in the soil profile (Swanton et al. 2000). The high-intensity tillage commonly associated with vegetable production results in a more even vertical distribution within the soil profile, and consequently, the presence of a persistent seedbank for many species. The presence of a persistent seedbank can slow the development of resistance or at least the dominance of a resistant ecotype (Norsworthy et al. 2012). In many vegetable crops, weed control during tillage operations is of secondary importance. For example, plasticulture production systems rely on tillage to level fields and prepare the beds for fumigation. Therefore, it is likely that most vegetable production systems will continue to rely on intensive tillage for the foreseeable future and that this will continue to be an important component of weed management.

Mechanical weed removal within the crop tends to be less intense and more complex than tillage operations between crops. It is beyond the scope of this paper to review the vast number of techniques and technologies that have been developed for weed control between and within crop rows. There is little doubt that the focus on mechanical weed removal implements within vegetables is associated with the lack of chemical management options. Tillage implements are effective, but the inability to weed between crop plants without causing crop damage limits adoption of some technologies. The recent development of precision weed removal technologies that utilize artificial intelligence for weed detection and a range of actuator types for weed removal is likely to transform how we view weed removal. Although adoption of these technologies is still limited, this approach will likely dominate the market over the long term.

BMP 9: Hand Weeding

Hand weeding has been extensively used throughout the history of agriculture to remove weeds from crops (McErlich and Boydston 2014). However, since the discovery and commercialization of synthetic herbicides, many growers across have readily adopted chemical tools for weed management (Gianessi 2013; Heap 2014; Hossain 2015; Owen 2016; Peterson et al. 2018; Shaw 2016). The widespread acceptance of herbicides for weed control has been necessitated, in part, by the migration of previously available labor forces from rural to urban environments (Gianessi 2013; Heap 2014; Hossain 2015; Owen 2016; Peterson et al. 2018; Shaw 2016).

Worldwide, most reported cases of herbicide resistance have occurred in agronomic commodities such as cotton, corn, soybean, and small grains (Heap 2021). This includes conventionally produced crops as well as systems that have adopted genetically engineered, herbicide resistant–trait technology, particularly crops with glyphosate-resistant varieties. The relatively few occurrences of resistance in vegetables are likely due to multiple factors, including limited numbers of registered products, frequent crop rotations, and despite an aging and shrinking labor force, the continued use of hand weeding (McErlich and Boydston 2014; Prather et al. 2000). "Botanical purity" may also necessitate manual labor for weed removal. For example, hand weeding in salad greens and fresh herb crops is necessary to ensure that unwanted vegetation does not reduce the quality of the salable product (McErlich and Boydston 2014).

In agronomic cropping systems, hand weeding has been suggested as a tool for controlling management escapes and preventing seed return to the soil seedbank, which can help mitigate or delay the development of herbicide resistance (Nalewaja 1999; Norsworthy et al. 2012). The adoption of hand weeding for the management of herbicide-resistant weeds, particularly glyphosate-resistant species, has been documented in the midsouthern, southeastern, and central United States (Prince et al. 2012; Riar et al. 2013; Sosnoskie and Culpepper 2014). Soybean consultants surveyed by Riar et al. (2013) reported up to 15% of production acres were being hand weeded to control glyphosate-resistant *A. palmeri*. Growers and county Extension agents in Georgia indicated that 53% to 66% of cotton acres were being hand weeded for *A. palmeri* management (Sosnoskie and Culpepper 2014). Results from a survey of 1,299 producers across 22 states showed that 67% of all respondents were actively controlling weed escapes and

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working to prevent seed set and return to the seedbank (Prince et al. 2012).

While hand weeding can reduce weed seed set and alter the rate at which seedbanks develop, the strategy is unlikely to be effective as a stand-alone practice in many situations (Hossain 2015; Riemens et al. 2007; Sosnoskie et al. 2014). Infrequent or delayed hand-weeding events can have significant negative effects on crop development and yield (Hossain 2015). While selection pressure and accompanying weed shifts are most frequently associated with respect to herbicide use and resistance development, it is important remember that weed adaptations are occurring in response to *all* weed control activities, including hand weeding (Bagavathiannan and Davis 2018; Barrett 1983; McElroy 2014). The most prominent example of this is the development of *Echinochloa crus-galli* subsp. *oryzicola* that has an upright growth habit and a white mid-rib, like rice. Genetic changes brought about by unintentional human selection pressure (also known as Vavilovian mimicry) have led to the rise of a variant of *E. crus-galli* that has evolved to escape hand-weeding efforts in flooded rice production systems (Barrett 1983; McErlich and Boydston 2014; Ye et al. 2019).

BMP 10: Crop Termination

Crop termination with herbicides such as paraquat is a common practice in many regions (Nascente et al. 2013; Palhano et al. 2018). Crop termination following harvest facilitates plastic removal and kills any weeds present. In some cases, crops are terminated with soil fumigants, such as metam-sodium, that provide broad-spectrum control of soilborne pathogens, nematodes, and weeds (Khatri et al. 2020; Radewald et al. 2004). Growers generally terminate all crops with the same SOAs, and as a result, herbicides such as paraquat are used multiple years in a row even when vegetable crops are rotated. Continued reliance on a single SOA to terminate weeds on an annual basis is likely to result in selection for resistance.

BMP 11: Movement of Plant Parts and Propagules

The movement of weed parts and propagules from one field to another has resulted in dispersal of herbicide-resistant weeds. Weed seed dispersal under natural conditions is generally limited to up to 5 m from the source (Verkaar et al. 1983). However, due to continuous movement of humans, weeds also were dispersed to distant places (Burton et al. 2006). Weed seed dispersal by machinery, waterways, and wild and domesticated animals also commonly occurs (Goddard et al. 2009; Traveset et al. 2001). In addition, intra- and interregional transport of animals grazed on resistant weed species, machinery, and waterways may have played an important role in the movement of weed seed into new regions. For example, approximately, 169 weed seeds m^{-2} were found in the soil seedbank after the manure from swine (*Sus domesticus* L.) was applied to the soil (Menalled et al. 2005). In a recent study, researchers found that commercial birdfeed is mixed with 29 different weed species in the United States, and seeds of the *Amaranthus* species were the most abundant (96%) (Oseland et al. 2020). Short- and long-distance movement of weed seeds can occur, and both are undesirable. However, long-distance movement is of great concern, as it leads to the establishment of a herbicide-resistant weed species in its nonnative region.

Recently, pollen-mediated gene flow has been reported as one of the potential sites of transfer of genetic information (alleles) from one plant to another compatible plant (Jhala et al. 2021; Sarangi et al. 2017). Even though gene flow is influenced by several factors, such as reproductive biology, management practices, and environmental conditions, it has been shown to contribute significantly to spread of herbicide resistance in *A. powellii* (Gaines et al. 2012), *A. tuberculatus* (Sarangi et al. 2017), *A. trifida* (Ganie and Jhala 2017), *C. canadensis* (Wang et al. 2017), and *C. album* (Gasquez 1985; Yerka et al. 2012), all of which are prominent weed species in vegetable production systems in the United States. The rate of gene flow is higher in *Amaranthus* and *Lolium* species compared with other species such as *C. album*, which requires short distances for pollen transfer (Gasquez 1985; Jhala et al. 2021). Once outcrossed, resistant alleles introgress in susceptible populations within a few generations (Gealy et al. 2003). The resistant species should be prevented from flowering to reduce gene flow and rapid spread of herbicide resistance. Alternate herbicide programs with crop rotation have been recommended for such scenarios, and early application of herbicides has been recommended to control these weeds at an early stage. The use of the stale seedbed technique before planting is very effective in reducing the soil seedbank of these herbicide-resistant weeds (Bond and Grundy 2001).

BMP 12: Management of Composts, Manures, and Plant Residue

Composts, mulches, crop residues, or manures are often used as fertilizers or weed suppressors in vegetable crops. The use of mulch or compost reduces the light available to the emerging seedling and in combination with toxic compounds present helps in weed suppression (Ozores-Hampton et al. 2001; Ramakrishna et al. 2006). However, these otherwise helpful measures sometimes are known to be the primary source of introduction of new or herbicide-resistant weed species to a field or a farm. Movement of herbicide-resistant weed seed among fields or regionally via machinery, compost, commercial seed stocks, feed, crop residues, or irrigation water is generally greater compared with natural seed dispersal (Beckie et al. 2019).

Animal grazing is considered an effective method of weed control in pastures. However, manure formed from the animals grazing in open pastures could be a carrier of herbicide-resistant weed seeds. Weed seeds can pass through the digestive tract and hence can be deposited to the soil seedbank and become troublesome (Blackshaw and Rode 1991; Pleasant and Schlather 1994; Wiese et al. 1998). For example, 52% seeds of *A. retroflexus* were reported to be viable after digestion and excretion (Blackshaw and Rode 1991). Moreover, livestock manure or hay/soil from pastures may carry herbicide residues that can cause injury to vegetable crops (Singh et al. 2019). These potential carryovers are generally sublethal doses of residual herbicides and thus play an important role in the evolution of herbicide resistance.

Therefore, it is critical to analyze the source of these alternative weed suppressors or compost materials. Use of soil or crop residues from fields with a known history of herbicide-resistant weeds should be avoided in freshly prepared vegetable plots. Deep strategic tillage, such as use of a moldboard plow every 4 to 8 yr, has been found to be effective in burying weed seeds to a considerable depth (Renton and Flower 2015). Weeds such as *A. powellii* lose more than 90% viability within 3 yr at greater soil depths (V Singh, unpublished data). Similarly, windrow burning of crop residues can reduce weed populations by 99% (Haring and Flessner 2018; Walsh and Newman 2007). These practices may help in management of composts, manures, and plant parts to ensure herbicide resistant weed free conditions.

We conclude this review by noting that herbicide resistance occurs in vegetable crops, but it is rarely studied or adequately funded, and resistance is likely to become an increasingly important issue. We have highlighted a range of management options that can slow the development of resistance, but resistance management is best achieved with the adoption of a diverse and effective IWM program.

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