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The Challenges of Specialty Crop Weed Control, Future Directions

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The process of labeling new herbicides for specialty crops has always been difficult. Progress in solving specialty crop weed control problems will likely be more challenging in the future. Major crops like corn, cotton, rice, soybean, and wheat are planted on millions of hectares, and most of these crops are treated with herbicides. In contrast, specialty crops (i.e., minor crops, e.g., container ornamentals or lettuce) are planted on 122,000 ha or less; thus, the potential value of herbicide sales is limited in these crops by the low number of hectares planted per crop. High crop value, small hectarage per crop, and generally marginal herbicide selectivity results in a high potential of liability for herbicide registrants and little incentive to label herbicides in these crops. The Interregional Project Number 4 (IR-4) program facilitates the registrations of pesticides on minor crops. Work needed to support pesticide tolerance in a given crop is conducted by IR-4 and cooperators. However, to develop new crop tolerances, the IR-4 process requires new herbicides. The success of glyphosate-resistant soybean has resulted in a less profitable herbicide market for all crops. In response, most primary pesticide manufacturers have reduced the size, or even eliminated herbicide discovery programs. As private industry slows or stops herbicide development, there will be fewer new minor-crop herbicides. Many questions face minor-crop weed scientists. For example, what are other practical solutions to control weeds in minor crops besides herbicides? Should research focus on development of competition models and decision thresholds or on weed removal tools such as robotics? What funding sources are available for minor-crop weed scientists? Are grant programs at the Federal level prepared to increase support for minor-crop weed research? Will university administrators replace retiring specialty crop weed scientists, knowing that their funding sources will produce little overhead? These questions require a response from all parties interested in specialty crop weed control.

Nomenclature: Corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; lettuce, *Lactuca sativa* L.; rice, *Oryza sativa* L.; soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

Key words: Specialty crops, minor crops, fruit, ornamentals, vegetables, labor shortages.

Sales of fruits, vegetables, and ornamentals compose nearly half of the total value of all U.S. field-grown crops (NASS 2002). These crops are referred to as minor crops or specialty crops, despite their great economic importance, because individual specialty crops are grown on 122,000 ha or fewer nationally (IR-4 2006). Because of higher labor input requirements, weed management programs for most minor crops are less efficient and more expensive than programs for the major crops such as field corn and soybean. Minor-crop producers generally rely on a small cadre of old herbicides with limited weed control spectrum, combined with mechanical cultivation and labor for hand weeding.

Current prospects for the future of weed control in minor crops are not encouraging. Despite the enormous economic impact of minor crops, they receive a disproportionately small fraction of the funding made available for weed research. For example, the U.S. Department of Agriculture (USDA) National Research Initiative had \$183 million in funding for 2006, yet not one of the research programs is directed at weed control for minor crops (NRI 2005). Advances in integrated weed management made in recent years for agronomic crops have not provided similar benefits in minor-crop weed control programs because of low tolerance for weed competition and the lack of remedial herbicides in minor crops (Norris 1992; Olson and Kidman 1992; Wiles 2004). Modified cultural practices such as delayed seeding or planting varieties on the basis of crop competitiveness to control weeds are not options for fresh produce such as lettuce because markets must be supplied on a daily basis with varieties selected for culinary rather than horticultural attributes (Buhler and Gunsolus 1996).

Statement of the Problem. Weed control programs in many specialty crops require high inputs. For example, many specialty crops are dependent on hand weeding for profitable production because of the lack of herbicides that control key weeds. Increasing weed control costs threaten continued production at current levels and future growth potential for specialty crops in the United States. Increasing labor costs continue to put the United States at a disadvantage relative to countries with lower labor costs, such as Mexico (Calvin et al. 2004; Martin 2007). We suggest that research is needed to increase the efficiency of specialty crop weed control programs if U.S. production of these crops is to be maintained. Administrators and those creating programs to fund agricultural research need to consider that the classification “minor crops” is very misleading. The term “minor” only refers to planted area and not economic value. To illustrate, vegetable crops were planted on about 800,000 ha in 2004 with a net value of \$10 billion compared with field corn grown on 30 million ha with a value of approximately \$25 billion (NASS 2004). Overall, the value of fruits, nuts, berries, herbs, nursery plants, and ornamentals, all classified as “minor crops,” is about \$41 billion, representing about 43% of the total crop value in the United States (NASS 2002). Furthermore, given increasing production costs for agronomic

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Table 1. Minor-crop herbicides and fumigants that have been lost or subject to regulatory action since 1980 in the United States and Canada (WSSA 2002b).

Acetochlor	Butylate	DCPA	Metham	Nitrofen	Terbacil
Alachlor	Chloramben	Diethatyl ethyl	Methyl bromide	Pebulate	
Amitrole	Chloroxuron	Diphenamid	Metobromuron	Propachlor	
Asulam	Clopyralid	EPTC	Monolinuron	Pyridate	
Atrazine	Cyanazine	Ioxynil	Niclofen	Solan	

crops in the United States, high-value crops likely will become more important in the future. Higher production costs and reduced profitability of agronomic crops in turn force growers to accept higher risks associated with specialty crops to remain profitable (Blank 1998). For example, sugar beet (*Beta vulgaris* L.) production in high–land value areas of coastal California has completely disappeared, replaced either by vegetable crops or wine grapes (CA-DFA 2006; Kaffka 1996). Small potential for sales and the high relative value of minor crops per hectare are disincentives faced by registrants who might develop new herbicides for them (Bell et al. 2000). Growers of minor crops who create niche produce markets exacerbate this. Such crops are usually planted on very small areas yet require a very high degree of weed control to maintain crop quality. Niche markets are usually ephemeral, further discouraging development of tailored technology.

Specialty crops have always had few herbicides available compared with the major agronomic crops grown in the United States. Development of new herbicides for specialty crops has largely been in the hands of public sector weed scientists who have evaluated herbicides already registered or under development for major crops to find those with adequate safety for one or more minor crops. Typical minor-crop herbicides were likely introduced more than 30 years ago. This contrasts with agronomic crops, in which advances in the efficiency of weed control systems, such as glyphosate-resistant soybean, are unparalleled in any specialty crop. Furthermore, many of these ''old'' specialty crop herbicides are subject to regulatory actions, such as the Food Quality Protection Act (Goldman 1997) and the Montreal Protocol (EPA 2004), and to regulation of volatile organic compounds (CA-DPR 2006b), which could result in the loss or severe restriction of products currently available to specialty crop producers. We are aware of more than 20 minor-crop herbicides previously registered in the United States and Canada that have been removed from the market or had their legal use severely restricted through regulatory action (Table 1). Often this has occurred with little or no attempt by manufacturers to defend the product because they had little economic incentive to do so. Liability is a major issue that has factored into many of these regulatory decisions; often a single liability claim or threat of such is sufficient for a registrant to withdraw a particular use. During this 20-yr period, the only new registrations, mostly section 18 (emergency use) and 24C state labels (special local needs), have been clethodim, rimsulfuron, mesotrione, halosulfuron, flumioxazin, oxyfluorfen, pendimethalin, clopyralid, sulfentrazone, and dimethenamid (Bell 1997; Maynard and Hochmuth 1997; Peachy 2007).

Prospects for new horticultural crop herbicide development are bleak. Success in finding new minor-crop herbicides is greatest when a large number of new herbicides are available for evaluation. Drastic attrition in the herbicide market brought on by the effects of glyphosate-resistant crops have reduced the incentive for development of new compounds, severely limiting new products with potential for minor crops (Duke 2005; Shaner 2000). The pesticide industry faces ever increasing financial barriers that must be crossed to justify development of a new herbicide (Gast 2008). For example, current estimates are that a product must have the potential for $185 to $200 million in annual sales to be worth the development cost, and very few pesticides fit these criteria (Gast 2008; L. Glascow, Syngenta, personal communication). Therefore, the historical approach of screening herbicides previously registered in agronomic crops, for natural tolerance in specialty crops, is unlikely to meet the future needs of growers. Here we argue for an expanded research focus and concomitant funding that goes far beyond traditional herbicide screening efforts toward the development of new weed management technologies and systems to meet the future needs of specialty crop growers.

Current Minor-Crop Herbicides. We have grouped 14 specific categories of minor crops into six categories: vegetables, tree and vine crops, bush berries, grass crops, miscellaneous crops such as tropical fruit, and ornamentals (IR-4 2006). The effectiveness of available herbicides varies by crop category.

Vegetable Crops. These include root crops such as red beet, tuber, and corm crops such as potato (*Solanum tuberosum* L.), bulb crops such as onion (*Allium cepa* L.), leafy greens such as lettuce, leaf petiole crops such as celery (*Apium graveolens* L.) or rhubarb (*Rheum* spp.), head and stem brassicas such as broccoli (*Brassica oleracea* L.), brassica greens such as mustard greens [*Brassica juncea* (L.)], legumes such as snap beans (*Phaseolus vulgaris* L.), fruiting vegetables such as tomato (*Solanum lycopersicum* L.), cucurbits such as cucumber (*Cucumis sativus* L.), grains such as sweet corn, and herbs and spices such as basil (*Ocimum basilicum* L.). To extensively review the status of each and every vegetable crop is beyond the scope of this paper. However, some generalizations to vegetable crops illustrate the scope and depth of the challenges facing minor-crop weed control specialists. Characteristically, herbicide tolerance in vegetables is low and can vary within a particular crop from cultivar to cultivar. One fresh-produce farm in Ohio grows more than 800 different cultivars of vegetables each year. Many vegetable crops are small-seeded and have seedlings that grow slowly with delicate tissues that are easily injured by a multitude of stresses, including herbicides. Great care must be taken to ensure that persistent soil residues of herbicides applied in previous years do not affect the myriad of vegetable crops that might be planted

Table 2. Herbicides by crop group, representative crop, typical herbicide by crop, and year of herbicide registration.

Crop group	Representative crop[a]	Primary herbicide (CA-DPR 2005)[b]	Herbicide registration year
Root crop	Carrot	Linuron	1966
Tuber and corm	Potato	*S*-metolachlor	1976
Leafy greens	Lettuce	Pronamide	1972
Head and stem brassicas	Broccoli	DCPA	1958
Brassica greens	Bok choy	DCPA	1958
Fruiting vegetable	Pepper	Napropamide	1972
Legume	Succulent bean	*S*-metolachlor	1976
Grains	Sweet corn	*S*-metolachlor	1976
Herbs and spices	Sweet basil	Metham	1954
Petiole	Celery	Prometryn	1964

[a] Bok choy, *Brassica rapa* L.; pepper, *Capsicum* spp.

[b] *S*-metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide.

after grain crops or a previous crop of vegetables or fruit. A few vegetables, such as carrot (*Daucus carota* L.) and celery, have very effective herbicides available in the form of linuron (*N*′-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea), metribuzin (4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one), and prometryn (*N*,*N*′-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine) (Smith 2005; Smith et al. 2005b). However even these herbicides are "dated"; like the "typical" minor-use herbicides described previously, most were registered over 30 years ago (Table 2), and crop tolerance is not always adequate. Sweet corn has benefited somewhat from the availability of herbicides developed for field corn, but until the registration of mesotrione, no highly selective herbicide was available to control triazine-resistant broadleaf weeds or Canada thistle [*Cirsium arvense* (L.) Scop.]. However, most vegetable crops have inadequate weed control with available herbicides. For example, spinach (*Spinacia oleracea* L.) grown for fresh-market production has only one herbicide, cycloate (*S*-ethyl cyclohexylethylcarbamothioate), available for use in California (Smith et al. 2005a). Cycloate is typical of minor-use herbicides, providing only partial weed control. Therefore, spinach producers must hand weed extensively to produce a crop. Furthermore, cycloate can injure spinach during warm conditions (Fennimore et al. 2001). Similarly, green onion (*Allium* spp.) is an important salad crop grown by fresh-market and wholesale vegetable producers throughout the United States. DCPA (dimethyl 2,3,5,6-tetrachloro-1,4-benzenedicarboxylate) is registered for use but has limited activity on broadleaf weeds and is not used at all on muck soils. Green onion grown on muck soils in the Midwest is a 45- to 60-d crop, from seeding to harvest, yet requires three hand weedings, each at a cost of $741/ha (B. Burma, Burma Farms Inc., personal communication). An effective broadleaf herbicide such as oxyfluorfen would eliminate the need for two hand weedings. Despite crop safety that meets the requirements of growers and their willingness to indemnify the registrant, the manufacturer of oxyfluorfen hesitates to support IR-4–sponsored food residue studies because of concerns over potential liability (Brian Brett, Dow AgroSciences, personal communication). Herb crops such as cilantro (*Coriandrum sativium* L.) have bensulide, which controls only a few weeds (Gowan 2007); therefore, cilantro growers use metham, which is expensive and subject to increasing regulatory restrictions (CA-DPR 2006a,b). Linuron could be available in cilantro within 2 to 3 yr (R. Sisco, IR-4, personal communication). The combination of few new herbicides to test within the IR-4 system and the potential for the loss of many older fumigants and herbicides, strongly suggests that vegetable crop weed control practices are at risk.

Trees and Vines. These crops include fruit trees, such as apples (*Malus domestica* Borkh.) and peaches [*Prunus persica* (L.) Batsch], as well as grapes (*Vitis* spp.). Tree and vine crops use directed sprays of glyphosate, paraquat alone or in combination with a residual herbicide such as simazine or oxyfluorfen. Finding selective herbicides for these crops has been easier than for vegetables because directed sprays that minimize herbicide application to foliage are used and because of the nature of these crops to root deeply. However like vegetables, few new registrations have been achieved in recent years with the exception of selective grass killers such as sethoxydim and fluazifop (Elmore et al. 1997). Tree fruits and vines are long-term plantings. Once established, there is little concern about effects of carryover potential from soil-active herbicides. However, permanency is a disadvantage in that repeated use of the same herbicides such as glyphosate, has led to resistance in rigid ryegrass (*Lolium rigidum* Gaudin) in California orchards (Simarmata et al. 2005) and more recently buckhorn plantain (*Plantago lancelota* L.) in South African orchards and vineyards (Heap 2008).

Within the tree and vine crop category, the most difficult weed control situation is in deciduous tree nurseries. Nursery sites that have made the transition from methyl bromide (bromomethane), which controls most weeds, to alternative fumigants such, as 1,3-dicloropropene (1,3-D) and metham, often experience inconsistent weed control. As a result, tree nursery producers have had to absorb higher weed control costs that might not be transferable to their customers (R. Wooley, Dave Wilson Nursery, personal communication).

Berries. For annual production strawberries (*Fragaria* × *ananassa* Duch.) there are several challenges, among them finding replacements for methyl bromide (Fennimore et al. 2003). Most strawberry fruit produced in California and Florida is grown on previously fumigated soils. In California, about 45% of the strawberry hectarage uses fumigants other than methyl bromide, which has led to increased herbicide use (CA-DPR 2006a; USDS 2006). Outside of California and the southeastern United States, strawberries are grown in a perennial matted row system without benefit of weed control from preplant fumigation and plastic mulch. These growers routinely rank weed control as their most serious cultural problem (Polter et al. 2005). Recent expansion of the label for terbacil, a very old herbicide, and new Section 24C and Section 18 labels for clopyralid and sulfentrazone, respectively, have helped. The IR-4 program was essential for achieving these registrations. However, it is worth noting that minor-crop weed scientists worked on the clopyralid registration from the late 1980s until 2003 before the first Section 24C was granted. Two years later, clopyralid is labeled in only a few states. The situation faced by blueberry (*Vaccinium* L.) and bramble (*Rubus* L.) growers is more severe. Diuron and simazine are the principal herbicides used; at rates of 2 to 4 kg ai/ha annually. Dichlobenil may be applied in mid-winter to suppress perennial grasses and broadleaf weeds; however, control of Canada thistle, milkweed (*Asclepias syriaca* L.), and field bindweed (*Convolvulus arvensis* L.) is inadequate, severely constraining long-term productivity of stands.

Ornamentals. Container ornamentals and field-grown cut flowers are examples of ornamental crops. Typical field-grown cut flowers are calla lily (*Zantedeschia* spp.), stock (*Matthiola* spp.), larkspur (*Delphinium* spp.) and hundreds of others, with numerous varieties of each (Schneider et al. 2003). Weeds are controlled in field-grown cut flowers with cultivation, hand weeding and fumigation (Elmore and Wilen 2000). These producers face numerous challenges, including the loss of methyl bromide for fumigation to control soilborne diseases, weeds, and volunteer bulbs from the previous crop (Schneider et al. 2003). Development of herbicides for these crops is very difficult because of the large number of crop species and numerous varieties within each crop. Because of the complications of finding herbicides with adequate crop selectivity on more than one crop, use of fumigants predominates as the method of weed control in field-grown cut flowers. Competition from offshore producers in low-cost labor markets requires that cut-flower growers remain very efficient. Therefore, it is necessary to limit hand weeding as much as possible to reduce costs.

Weed control problems in container nurseries include species with wind-blown seed, such as common groundsel (*Senecio vulgaris* L.) and liverwort (*Marchantia polymorpha* L.) (Elmore and Wilen 2000). Weed control in container ornamentals is accomplished through chemical fumigation with metham or dazomet or by steam sterilization. Postplant weed control programs consist of hand weeding and herbicides such as oxyfluorfen and isoxaben.

Miscellaneous Crops. In this category we include tropical fruit crops such as avocado (*Persea americana* Mill.), coffee (*Coffea* L.), and papaya (*Carica papaya* L.). Also, numerous crops are planted on limited areas, such as artichoke (*Cynara scolymus* L.), prickly pear cactus (*Opuntia* Mill., grown for fruit), and dates (*Phoenix dactylifera* L.). Some of these crops (e.g., prickly pear cactus) have no herbicides registered, and the only means of weed control in these crops is by tillage or hand weeding (CA-DPR 2006a; R. Smith, University of California, personal communication). It is unlikely that a potential herbicide for a miscellaneous crop would ever be prioritized for research in the IR-4 system because they are rarely grown in more than a small part of one state. Support from two or more regions in the United States is generally needed for a project to receive a high prioritization (IR-4 2006).

The crops with the greatest weed management research needs are vegetable crops, field-grown ornamentals, and miscellaneous crops. These crops either do not have the necessary herbicides and are heavily dependent on fumigation and hand weeding, or soon will lose the tools they currently have to regulatory actions.

Effects of Regulatory Action. Many possible regulatory actions could affect herbicide availability in minor crops. The Food Quality Protection Act (FQPA) of 1996 requires the review of all pesticide tolerances (Bell et al. 2000; Goldman 1997), but thus far the effect of FQPA on the availability of minor-crop herbicides has been minimal. When fully implemented, the phase-out of methyl bromide as required by the Montreal Protocol (EPA 2004) could cause severe negative consequences to weed control. Methyl bromide provides excellent control of weeds such as yellow and purple nutsedge (*Cyperus esculentus* L. and *C. rotundus* L.), a major reason why this fumigant is used in Florida tomato production (Gilreath and Santos 2004; Locascio et al. 1997).

It is anticipated that the phase-out of methyl bromide will continue to lead to development of new weed control problems that need to be addressed. Replacements identified for methyl bromide have thus far centered on fumigants such as chloropicrin, metham, or combinations of chloropicrin and 1,3-dichloropropene (1,3-D), as well as herbicides such as EPTC (*S*-ethyl dipropyl carbamothioate) (Santos et al. 2006). Many people, however, believe that fumigants offer only short-term solutions to the long-term problems that necessitate their use. Concern for off-site movement of volatile fumigants dissipating into the air from treated soil has heightened concern about the future of fumigation in highly urbanized states like California (CA-DPR 2006b). Recent high-profile cases in which dozens of people claim to have suffered illnesses after fumigant exposure have further jeopardized use of these products because political and regulatory pressure to reduce offsite movement is intense (Segawa 2005). California already limits the use of 1,3-D per township (93.2 km^2), a key methyl bromide replacement (Carpenter et al. 2001). Although metham is currently labeled for use on all crops (Amvac 2007) and in California is used in carrot and spinach and herbs such as cilantro (CA-DPR 2006a), new restrictions on volatile organic compounds will likely lead to further restrictions on the use of metham in California (CA-DPR 2006b).

Effects of Increasing Labor Costs on Hand Weeding. Hand weeding is among the most expensive weed control tools (Bolda et al. 2005). Increasing limits on noncitizen migrant labor and competition for labor from nonagricultural industries all contribute toward labor scarcity and increasing cost of labor (Blank 1998; Levine 2007; Martin, 2007). Technology such as machine-vision robotics might eventually allow some inputs to be replaced, but it remains to be seen what the final impact will be (Downey et al. 2004). Crops such as broccoli, lettuce, and strawberry all require hand weeding (Tourte and Smith 2001); increasing labor costs will drive up production costs unless labor inputs can be replaced with other tools, such as new herbicides that control more weeds and precision cultivators. Otherwise, it is likely that domestic requirements for such crops will increasingly transfer to foreign suppliers, where labor costs are more in keeping with a low-cost food economy. For example, the majority of green onions consumed in the United States shifted from domestic production toward Mexican production in the 1980s because of lower labor costs in Mexico (Calvin et al. 2004).

Interregional Project 4. This agency, founded in 1963 as interregional project number 4 (IR-4), has the set objective to secure food use tolerances for minor crops so that pesticides can be labeled. The process to register herbicides for minor crops is dependent on requests by growers, commodity groups, or university and USDA scientists to make project requests (see Kunkel et al. 2008 for details on IR-4). The requests are prioritized at the annual food use workshop as A, B, C, or D, with A the highest priority and project most likely to be conducted. Category B priorities can be conducted providing resources are sufficient. The C priority is a holding category, and D priority terminates consideration of a project (IR-4 2006). Prioritization at the food use workshop is conducted by representatives from states in each of the four IR-4–designated regions: North Central, Northeast, South, and West. Herbicide uses are more likely to be ranked as an A priority if more than one region supports the project; thus, low-hectarage ultraminor crops such as prickly pear cactus are difficult to move into the A category because they are not grown in more than one region. As described above, there is no shortage of need for new herbicide tools in minor specialty crops, but there *is* a shortage of herbicides for which specialty crops have adequate tolerance. The current situation in the agricultural chemical industry is such that fewer new herbicides are being developed than in the past. Therefore, the process of matching a herbicide to a crop with natural tolerance is becoming more difficult. The IR-4 process works when the flow of new food use tolerance requests for herbicides is continuous. Fewer new herbicides in development results in an IR-4 process less likely to provide new specialty crop weed control tools.

Long-Term Implications of Inadequate Funding for Development of New Weed Control Technology for Minor Crops. As illustrated previously, minor-crop weed control research is severely underfunded, failing to even distantly match the economic impact of growing these crops in the United States. In particular, very few programs pay administrative costs that will support the most urgently needed, highly practical research. This situation creates a double jeopardy. Current scientists hired to conduct grower-oriented research face severe challenges in meeting their responsibilities and might be judged negatively by their peers for emphasis on applied research. Moreover, this situation threatens the future ability of the weed science discipline to address the weed control needs of American minor-crop farmers. As the most experienced minor-crop weed scientists in the country contemplate retirement, college deans contemplate the future of their positions. It is unlikely that a scientist oriented toward weed control will replace many of these individuals.

Future Research Directions in Specialty Crops. Given all of the constraints to the registration of herbicides in minor crops described above and increasing limits on the use of fumigants, what are productive options for weed scientists to pursue to create new weed control tools? The purpose of this section is not to go into great detail about these research topics, but to highlight some ideas that are not discussed at length in the following symposium papers.

Breeding for Herbicide Tolerance. This approach involves the development of herbicide tolerance in specialty crops in which natural herbicide tolerance is inadequate. An example of this approach was used to develop imazamox resistance in wheat (Bond et al. 2005). Herbicide-resistant specialty crops can also result from genetic modifications conducted to achieve a different end. ATTRIBUTE Insect Protected Sweet Corn™ varieties[1] are genetically modified to produce a delta-endotoxin protein (*Bacillus thuringiensis* CryIAb) that confers a high level of resistance to feeding by the corn earworm and the European corn borer and moderate resistance to feeding by the fall armyworm (*Spodoptera frugiperda* J.E. Smith) (Lynch et al. 1999). ATTRIBUTE varieties are widely grown throughout the United States, mostly marketed direct to the consumer. These also contain a selectable marker gene that codes for the enzyme phosphinothricin-acetyl transferase (PAT), which provides acceptable tolerance to the broad-spectrum, postemergence herbicide glufosinate (Doohan et al. 2002; Lynch et al. 1999). Glufosinate is applied postemergence (POST) and degrades rapidly in agricultural soils, with an estimated half-life of 7 d; therefore, damage to rotational vegetable crops is unlikely (WSSA 2002a). Glufosinate controls 24 species of annual weeds, including triazine-resistant biotypes (Bayer 2007) and would provide improved flexibility of crop and weed management to growers; however, this use has never been registered because of concerns that consumers might react negatively. Development of transgenic glyphosate-resistant specialty crops such as lettuce (Fennimore and Umeda 2003) is not an option for specialty crops because of current policies of produce buyers that prohibit purchase of genetically modified organism (GMO) crops (Shane Sampels, Sysco, personal communication). However, conventional breeding for herbicide tolerance in vegetable crops, similar to the "Clearfield" approach, is an option that has not been explored in vegetables (Fennimore et al. 2005). It might be possible to use mutagenesis breeding to increase the tolerance of minor crops to existing herbicides. In this approach, vegetable crop seed would be treated with a mutagen such as ethyl methansulfonate (EMS) to attempt to induce increased herbicide tolerance (Sigurbjornsson 1983). This approach need not be limited to searching for mutants tolerant to imidazolinone or to sulfonylurea herbicides, but also to select individuals that are tolerant to other classes of herbicides. The idea of conventional breeding for increased herbicide tolerance in vegetables has appeal, in that it would allow minor-crop weed scientists to overcome the slow pace of new herbicide development with the use of existing herbicides to develop new weed management programs and yet avoid the pitfalls of transgenic herbicide-resistant crops. Careful planning would be necessary to avoid the use of the same herbicides in several vegetable crops to limit weed population shifts and the development of herbicide-resistant weeds. Ideally, rotational crops would use herbicides with different modes of action, and the use of mechanical weeding would be retained.

Robotic Technology. Machine-guided cultivation is promising and is already being adopted by growers (Downey et al. 2004). Commercially available machine-vision guidance involves guiding the fine movements of the cultivator, thus allowing for more rapid and accurate operation. A typical machine, such as the Eco-Dan® guidance system[2] uses a digital color camera that takes 25 pictures per second of the green plant row directly beneath it. These pictures are processed by a computer to establish the row centerline. As the row centerline shifts, the computer signals a control valve to move a hydraulic cylinder right or left to keep the implement in the correct working position over the row. The Eco-Dan guidance system can differentiate between plants within the row and random weed patterns. One labor-saving advantage of machine-vision guidance is that it allows the cultivator to drive faster and cover more acres per day than for a conventional cultivator. Another possible labor savings from this equipment might be cultivation closer to the seedline so that more weeds are removed and hand weeding costs are reduced (Fennimore et al. 2007). The next step is to remove weeds in the seedline. In this approach, machine-vision technology is required that can distinguish between a crop and a weed so the cultivator can selectively remove the weed. The technology capable of recognition and robotic removal of weeds is available in research prototypes, but this technology is not yet commercially available (Lee et al. 1999; and see the paper by Slaughter et al. [2008] on mechanical weed recognition).

Biocontrol and Allelopathy. Other than Devine (*Phytopthora palmivora*) for control of stranglevine [*Morrenia odorata* (Hook. et Arn.) Lindl.] in citrus, we are aware of no other biocontrol agent available for weed control in specialty crops (Encore 2006). To date, biocontrol of weeds has had little effect on minor-crop weed control programs. Biocontrol of weed seedlings and weed seedbanks in the soil might be more promising than the use of foliar pathogens (Gallandt et al. 1999). Effects of cover crops and organic amendments clearly reduce weed populations by suppressing weed emergence (Brennan and Smith 2005; Haramoto and Gallandt 2005) or by enhancing soil microbe populations that prey on weed seedbanks (Fennimore and Jackson 2003). However, understanding the interactions between organic amendments, soil microbial communities, and weeds is complex and not well understood. This is an area with considerable potential to improve weed control, not just for minor crops, but for all crops.

A considerable amount of interest has been shown in the use of *Brassica* spp. green manure crops to smother weeds or to inhibit weed emergence (Haramoto and Gallandt 2005). These cover crops suppress weeds, but high levels of *Brassica* spp. cover crop residues might not be suited for horticultural crops. For instance, rapeseed foliage incorporated into the soil controlled common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) to a level nearly equal that of a standard herbicide treatment (Boydston and Hang 1995; Krishnan et al. 1998). Researchers have measured small reductions in weed densities in lettuce (R. F. Smith, personal communication) or no change in weed densities (Haramoto and Gallandt 2005). The levels of isothiocyanates (ITCs) that are found in soils after incorporation of mustard [i.e., *Brassica hirta* Moench, *B. juncea* (L.) Czern.] cover crop residues are typically much lower than levels of ITCs applied as commercial fumigants—for example, metham. The equivalent ITC content of mustard cover crops were determined and found to be equivalent to 8 to 10.8 kg/ha of metham per acre (R. F. Smith, personal communication). By comparison, labeled rates of metham fall between 176 and 352 kg/ha (Amvac 2007). The small amount of biofumigant that is contained in mustard cover crops could explain the low effect of mustard cover crops on weeds (Haramoto and Gallandt 2005). However, if breeders can increase the concentrations of ITCs in mustard cover crops, then it might be possible to realize better weed control (Norsworthy and Meehan, 2005).

Organic Production of Minor Crops. During the 1990s, the sales of organic foods increased at about 20% annually. About 20% of certified organic acreage is used for vegetable production or in orchards (Klonsky 2000). Organic minor-crop producers of course must manage weeds without the use of synthetic herbicides, and are heavily dependent on cultivation and hand weeding to manage weeds. Organic vegetable producers incur considerable labor expense for hand weeding, and costs are increasing (Gaskell et al. 2000). For example, hand weeding and cultivation costs involved in the production of organic leaf lettuce in California were estimated at $842/ha (Tourte et al. 2004). As fuel costs increase, the cost of propane flaming for weed control also increases. Virtually any aspects of specialty crop weed management research (e.g., robotic weed removal) would have utility in both conventional and organic production systems, with the exception of research on synthetic herbicides. Robotic devices are needed to reduce hand weeding costs, and organic-compliant herbicides are needed that are more efficient at removing weeds in the preparation of a stale seedbed than tillage and propane (Boyd et al. 2006). The question is whether public sector minor-crop weed scientists have the time and resources to meet the needs of both conventional and organic minor-crop producers and their challenging weed management problems.

Integrated Weed Management. The goal of integrated weed management is to use information about weed ecology and biology to develop methods of weed management that are focused on short- and long-term effects on weed populations (Buhler 1999). Much weed ecology research has been directed at determination of economic thresholds—that is, estimation of the weed density at which the benefit derived from herbicide application equals the cost of control (Swanton et al. 1999). However, few minor-crop producers practice integrated weed management, simply because the cost of weed control

Table 3. Relative weed control expenses in field corn and lettuce and percentage of weed control cost relative to gross crop value.

Weeding inputs	Field corn (Brittan et al. 2004)	Lettuce (Tourte and Smith 2001)	Raspberry (Bolda et al. 2005)[a]
		Cost $/ha	
Herbicide/fumigant	59	86	2,038
Cultivation	15	67	0
Hand weeding	0	279	921
Total weed cost	74	422	2,959
Crop value	1,235	16,796–20,995	177,840
Weed cost %	6.0	2.6–2.1	1.7

[a] *Rubus* spp.

is relatively low compared with the value of the crop. The value of savings from practices such as decision tools and economic thresholds is simply not worth the risk compared with the value of the specialty crop (Table 3). Because of the high value of most minor crops and the potential for buildup of foliar and soilborne pathogens in weed hosts (Vallad et al. 2005), the risks of not controlling weeds is simply too great in high-value crops. Many vegetable producers in California practice the zero-threshold concept (Norris 1999) and try to remove all weeds. However, increasing costs for fuel and labor make this goal more and more difficult to attain. This is why there continues to be interest by growers in the registration of new herbicides for minor crops, in that these products are among the most cost effective means of weed control. Yet very few new herbicides are in development for these crops. The prospect in the short term is low that glyphosate resistance will be conferred on specialty crops. We suggest that more resources should be focused on novel means to kill weeds chemically and by robotic cultivators, as well as to manage seedbanks with biocontrol agents.

Emphasis on the study of weed ecology in major crops (Mortensen et al. 2000) is appropriate where weed control inputs and crop values are low and the major cost of weed control inputs is herbicides. In major crops, there are many choices of excellent herbicides and the emphasis is on maintaining high levels of weed control with these products and yet avoid the development of herbicide-resistant weeds. In minor crops, crop values are often high, and herbicides (if available) represent a minor portion of the weed control costs compared with labor and machine costs for hand weeding and cultivation. Hand weeding, fumigation, and cultivation provide consistently high levels of weed control. Replacements for these practices will need to control weeds as consistently and effectively as hand weeding, albeit in a more cost-effective manner. Minor-crop weed control programs need more effective herbicides as well as similar cost-effective tools so that producers can control or reduce expensive hand weeding costs.

Minor crops are worth nearly half of the total value of all U.S. agriculture, yet weed management programs for minor crops are far less efficient than for major crops. Progress in addressing these deficiencies has been impeded by the combined lack of corporate and government funding for research. Accordingly, American minor-crop farmers are faced with mounting challenges to profitability, and production continues to shift to lower-cost foreign producers. Minor-crop weed control programs not only need new herbicides, but also similarly cost-effective tools such as robotic cultivators. The most urgent need in specialty crops is to replace hand weeding. However, replacements for hand weeding must be safe for the crop and not increase economic risk. It is time for industry, university, USDA researchers, and policy makers to come together and advance rational weed management research objectives for minor crops to find ways to fund productive research, and then to transfer this technology to minor-crop producers.

Sources of Materials

[1] ATTRIBUTE Insect Protected Sweet Corn, Syngenta Seeds, Boise, ID.

[2] Eco-Dan guidance system, Eco-Dan A/S, Kvistgaard, Denmark.

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