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Ecologically sustainable weed management: How do we get from proof-of-concept to adoption?

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Abstract. Weed management is a critically important activity on both agricultural and non-agricultural lands, but it is faced with a daunting set of challenges: environmental damage caused by control practices, weed resistance to herbicides, accelerated rates of weed dispersal through global trade, and greater weed impacts due to changes in climate and land use. Broad-scale use of new approaches is needed if weed management is to be successful in the coming era. We examine three approaches likely to prove useful for addressing current and future challenges from weeds: diversifying weed management strategies with multiple complementary tactics, developing crop genotypes for enhanced weed suppression, and tailoring management strategies to better accommodate variability in weed spatial distributions. In all three cases, proof-of-concept has long been demonstrated and considerable scientific innovations have been made, but uptake by farmers and land managers has been extremely limited. Impediments to employing these and other ecologically based approaches include inadequate or inappropriate government policy instruments, a lack of market mechanisms, and a paucity of social infrastructure with which to influence learning, decision-making, and actions by farmers and land managers. We offer examples of how these impediments are being addressed in different parts of the world, but note that there is no clear formula for determining which sets of policies, market mechanisms, and educational activities will be effective in various locations. Implementing new approaches for weed management will require multidisciplinary teams comprised of scientists, engineers, economists, sociologists, educators, farmers, land managers, industry personnel, policy makers, and others willing to focus on weeds within whole farming systems and land management units.

Key words: diversified weed management strategies; herbicide resistance; multidisciplinary research; outreach; site-specific weed management; weed ecology; weed-suppressive crop genotypes.

Introduction

Despite the use of considerable amounts of sophisticated chemical, mechanical, and genetic technologies dedicated to weed control, weeds remain key threats to crop productivity and profitability in both developed and developing countries (Oerke 2006). In rangelands and natural ecosystems, invasive plants (which we consider here as weeds) increasingly threaten biological diversity and disrupt ecological processes required to provide critical ecosystem services (Ehrenfeld 2010). Environmental and social contexts have always affected the damage that results from weeds and the strategies used to manage them. As those contexts change with more rapid shifts in land use and climate, greater demands for food production, and increased expectations for environmental protection, new ways are needed to manage weeds effectively.

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In this article, we review salient challenges posed by weeds, including unintended environmental effects of weed control practices, herbicide resistance in weed species, and increasing impacts of weeds in agricultural and non-agricultural areas due to greater international and regional trade, climate change, altered disturbance patterns, and other factors. We examine, as case studies, three approaches that are likely to prove useful for addressing current and future challenges from weeds: diversifying weed management strategies with multiple complementary tactics, developing crop genotypes for enhanced weed suppression, and tailoring management strategies to better accommodate variability in weed spatial distributions. Drawing on examples from both industrialized and developing countries, we then consider how adoption and implementation of such approaches might be affected by changes in government policy, shifts in market-related actions of agricultural processors and retailers, and greater attention to learning and decision-making by farmers and land managers.

The concepts and examples we offer stem from discussions that took place during a workshop convened in Benasque, Spain, in June 2014 that included researchers from five continents with experience in both agricultural and non-agricultural systems. Based on recommendations arising from a similar meeting in 2012 (Ward et al. 2014), participants in the 2014 workshop represented both biological and social science disciplines. Our intent here is to promote further discussion and collaboration between investigators and practitioners from a wide range of vocations, and to identify weed-related research topics that merit attention.

The Present Situation

Herbicide use and fate in the environment

Worldwide, herbicides comprise the majority of pesticide sales and use, and now pervade the production of staple crops in many countries. An estimated 950000 Mg of herbicide active ingredients valued at US$ 15.5 billion were used globally in 2007 (Grube et al. 2011). The trend for herbicide use is distinctly upward, with the worldwide herbicide market in 2016 projected to increase 50% over the level in 2002 (Gianessi 2013). Use of herbicides in farming systems has, in many cases, increased farm profitability, facilitated the adoption of reduced tillage practices that contribute to soil and water conservation, increased farm labor efficiency, and improved farmers' lifestyles (Gianessi and Reigner 2007, Pannell et al. 2011, Gianessi 2013, Zimdahl 2013). However, heavy reliance on these materials has also resulted in cases of environmental contamination.

In terrestrial systems, herbicides can move from sites of application via surface water runoff, groundwater leaching, aerial drift, and volatilization (Prueger et al. 2005, Shipitalo and Owens 2006, Weber et al. 2006, Gish et al. 2012). Depending on the particular materials used, application methods, and specific environmental conditions (e.g., soil and hydrogeological characteristics, precipitation patterns, wind speed, and topography), the scale of herbicide transport can range from centimeters to kilometers. In a review of data concerning off-site movement of herbicides, Gish et al. (2012) noted that loss of herbicides in run-off typically accounts for 1–4% of the mass of applied materials and that losses via leaching are generally <1%. In contrast, losses of herbicides via aerial drift and volatilization can be considerably greater, with typical losses for many products in the range of 5–25%; in exceptional circumstances, losses to the atmosphere may exceed 90% (Gish et al. 2011, 2012). Once in the atmosphere, herbicides can be deposited in non-targeted areas through both wet and dry deposition processes (Kuang et al. 2003, Vogel et al. 2008, Chang et al. 2011).

Transport of herbicides and subsequent exposure to non-target organisms have led to multiple concerns. Herbicides are commonly detected in surface and ground water in agricultural regions of the United States, Europe, and Japan with concentrations sometimes exceeding protection standards for human health and aquatic organisms (Gilliom et al. 2006, Masía et al. 2013, Narushima et al. 2014). Increased precipitation and droughts resulting from climate change have the potential to increase herbicide run-off and concentrations in water bodies, respectively, thus exacerbating environmental contamination and threats to human health and non-target organisms. Herbicide drift during application and volatilization following application can result in substantial injury to non-target crops and non-crop vegetation, especially at reproductive stages (Riemens et al. 2008, Mortensen et al. 2012, Boutin et al. 2014), and can alter insect communities dependent on floral resources and plant habitat (Egan et al. 2014). Herbicide movement in air (as vapor, liquid, or within soil particles) is also a key concern for organic farmers since contamination of organic fields from conventionally managed farms upwind can result in loss of certification and market premiums. Effects of herbicides on human health are contentious. For example, glyphosate, the herbicide with the highest global production volume, was classified by the U.S. Environmental Protection Agency (1993) as not posing "unreasonable risks or adverse effects to humans or the environment." A registration review conducted in 2001 in the European Union reached conclusions similar to those in the United States regarding glyphosate's animal and human safety, but identified protection of groundwater during non-crop use as an important concern (International Agency for Research on Cancer 2015). Although glyphosate is not considered a carcinogen in the United States (Henderson et al. 2010), it was recently classified by the World Health Organization's International Agency for Research on Cancer as "probably carcinogenic to humans" (Guyton et al. 2015).

Herbicide resistance in weeds

Repeated exposure of weed populations to herbicides can select for resistance, the heritable ability of plants to survive and reproduce despite receiving doses that are normally lethal. Weed resistance to herbicides has been documented for populations of at least 240 weed species worldwide, and for 22 of the 25 known groups of herbicide chemistries (Heap 2015). Herbicide resistance can evolve due to genetically based variation in biochemical target sites (Powles and Yu 2010), and individuals of certain weed species have been shown to have "stacks" of genes conferring separate resistances to multiple herbicides with different sites of action (Tranel et al. 2011, Heap 2015). Populations of *Amaranthus* spp. with multiple herbicide resistances (Fig. 1A) have become especially challenging in the Midwestern and Southern United States (Owen et al. 2014). Weed populations may also evolve enhanced capacity in particular metabolic pathways to detoxify multiple classes of herbicides, including those to which they have never been exposed (cross-resistance; Yu and Powles 2014). In an extreme case, a population of rigid ryegrass (*Lolium rigidum*) in Australia has been found to be resistant to 11 separate classes of herbicides (Heap 2015), largely or entirely due to metabolic cross-resistance (Yu and Powles 2014).

As existing herbicide products fail due to the evolution of resistance, chemical weed control options are shrinking, since no new classes of herbicide chemistry have been introduced for almost 30 years (Heap 2015). Concomitantly, in regions such as the European Union, various herbicides in current use are being removed from the marketplace through regulation due to concerns over environmental and human health impacts (European Commission 2009). Herbicide resistance in weeds is also a difficult area-wide socioeconomic problem because resistance genes are not sessile; they can spread from one farm to another through the movement of pollen and seeds (Ervin and Jussaume 2014). Thus, decisions and actions by individual farmers can contribute to resistance problems on surrounding farms.

The speed and scale with which herbicide resistance problems can occur in agricultural weeds are well illustrated by the history of acetolactase synthase (ALS) inhibitor herbicides and of glyphosate, the sole herbicide classified as an enolpyruvyl shikimate-3-phosphate synthase (EPSPS) inhibitor. Acetolactase synthase inhibitors were introduced commercially in the 1980's, and 56 different herbicidal chemicals in the group are registered worldwide (Heap 2015). Various ALS inhibitors have been used for weed control in all major field crops, including corn, small grains, cotton, pasture, peanut, and soybean (Vencill et al. 2012). Weed resistance to ALS inhibitors appeared rapidly under field conditions, and populations of at least 157 weed species are presently known to be resistant to these herbicides, due mostly to mutations that prevent one or more chemicals in the group from inhibiting activity of the target enzyme

Fig. 1. Weeds infesting agricultural and non-agricultural lands. (A) Palmer amaranth (*Amaranthus palmeri*) infesting cotton. Many populations of *A. palmeri* are resistant to multiple herbicide sites of action. Photograph courtesy of L. Steckel. (B) Parthenium weed (*Parthenium hysterophorus*) has spread from the Americas to Africa, Asia, Australia, and Oceania. Photograph courtesy of B. Rayner, © Western Australian Agriculture Authority. (C) After its introduction from Eurasia in the mid-1800s, yellow starthistle (*Centaurea solstitialis*) now infests millions of hectares in western North America. Photograph courtesy of J. DiTomaso. (D) Giant sensitive tree (*Mimosa pigra)*, native to the American tropics, forms dense thickets in Australia. Photo courtesy of W. Djatmiko.

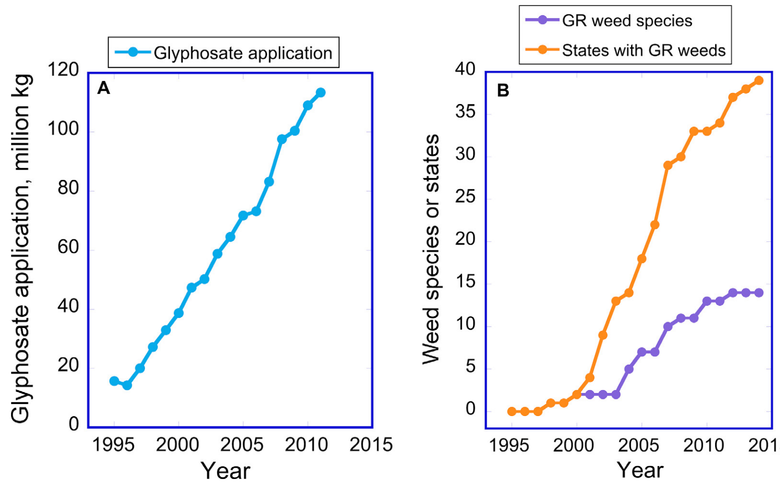

Fig. 2. (A) Agricultural use of glyphosate in the United States, 1995–2011. (B) The number of weed species with glyphosate-resistant (GR) populations found in the United States and the number of states infested with such populations, 1995–2014. Data from the U.S. Geological Survey (2015), Heap (2015).

(Vencill et al. 2012, Heap 2015). Although ALS inhibitors are still in use, resistant weeds have challenged their efficacy in most of the world's major crop production regions (Heap 2015).

When introduced in the 1970s, glyphosate was used to control a broad spectrum of weed species, but was also fatal to crops if they were sprayed. Consequently, it typically was applied before or after crops were present in the field. Glyphosate use increased dramatically in countries like the United States with the introduction in 1996 of transgenic crop genotypes resistant to its effects (Fig. 2A). However, the rapid expansion of reliance on glyphosate in United States agriculture, and elsewhere, has been met with concomitant increases in the number and geographic extent of weeds that have evolved resistance to it (Fig. 2B). Most glyphosate-resistant weeds are resistant via non-target site mechanisms, such as compartmentation of the herbicide within vacuoles where it is inactive (Vencill et al. 2012). Worldwide, populations of 31 weed species are known to be glyphosate-resistant; 15 of these have populations exhibiting resistance to up to four herbicide sites of action in addition to that targeted by glyphosate (Heap 2015).

Invasive plants in rangelands and natural ecosystems

Although precise quantitative assessments of the ecological, economic, and health costs of invasive plants are generally lacking (Barney et al. 2013), existing estimates indicate such impacts are large. Invasive alien plants and a smaller set of undesirable native species cause an estimated US$ 2 billion of losses per year on 400 million hectares of United States rangelands by lowering yield and quality of forage, interfering with grazing, poisoning animals, reducing land value, altering wildlife habitat, depleting and degrading soil and water resources, and reducing plant and animal diversity (DiTomaso 2000). Parthenium weed (*Parthenium hysterophorus*) (Fig. 1B), which has spread from North and South America to 34 countries in Africa, Asia, Australia, and Oceania, has been estimated to cost farmers and pastoralists in Queensland, Australia, over $A 100 million per year, and can cause severe allergic reactions in people (Adkins and Shabbir 2014) and taint the milk of cows that have grazed on fields containing it.

Herbicides can be very cost-effective in the early stages of invasion management, but once invaders are widespread, biological control may become the only hope. Biocontrol agents can disperse over large areas and through inaccessible terrain; however, the initial investment is often too large for public decision-makers, and agents often fail to establish or achieve acceptable results (Crawley 1989). In many cases, by the time problems with non-arable weeds are recognized, large areas of land are already infested and costs of removal or control may be high relative to the productive capacity of the land infested (DiTomaso 2000, Seabloom et al. 2013); effective suppression of populations will then be nearly impossible. Yellow starthistle (*Centaurea solstitialis*) (Fig. 1C), an annual herb that was introduced into California from Eurasia in the mid-1800s, now infests 15–22% of that state's surface area, at least 6 million hectares, and is present in 56 of the state's 58 counties, where it forms dense stands that displace desirable vegetation in natural areas and rangelands (DiTomaso et al. 2000). Various aspects of climate change, including greater atmospheric CO_2 concentration and increased nitrogen deposition, appear to foster the increasing prevalence of *C. solstitialis* throughout western North America (Dukes et al. 2011). The broad areal extent of this species coupled with changing environmental conditions mean that short-term local suppression efforts can easily be followed by re-infestation from surrounding source populations.

Decisions and actions by individual land managers can strongly affect the severity of weed infestations over large areas. Coutts et al. (2013) found that for two weedy grass species in Australian pastoral areas, *Nasella trichotoma* and *Eragrostis curvula*, if as few as 10% of land managers failed to control these species, long-distance dispersal from infested sites increased the invasion risk for most of the surrounding landscape. Increasing levels of international and interregional trade and transport, coupled with environmental factors such as climatic change and soil disturbance can also facilitate the spread of weeds (Meyerson and Mooney 2007). Since its introduction to Europe in the mid-1800s, *Ambrosia artemisiifolia*, an annual broadleaf weed that is native to North America, has spread rapidly throughout the region with the expansion of intensive farming systems and associated soil disturbance (Smith et al. 2013). It is estimated that in areas with high infestation levels, such as Hungary and Austria, the medical costs of allergic reactions to its pollen are € 110 and 88 million per year, respectively (Gerber et al. 2011). Agricultural yield losses due to *A. artemisiifolia* were estimated at € 130 million per year for Hungary alone (Kémives et al. 2006).

Thus, key challenges for invasive plant management include region-wide prevention of the arrival, establishment and dispersal of invaders, and the development of cost-effective, socially engaged strategies for treating areas with existing infestations. The latter challenge is further complicated by the need to limit environmental damage caused by control measures themselves (Buckley and Han 2014). In some cases, biocontrol agents released to suppress invasive plants have then attacked desirable native plant species (Mack et al. 2000), or have created shifts in food web relations among predators and parasitoids that result in undesirable losses of native insect species (Caravalheiro et al. 2008). Mechanical and chemical removal of invasive plants can also result in declines in desired native birds that utilize the invaders, as is the case for the endangered California clapper rail (*Rallus longirostris obsoletus*), which nests in San Francisco Bay in patches of invasive cordgrass (*Spartina alterniflora* × *S. foliosa*) (Lampert et al. 2014). Addressing these types of unintended effects will require new approaches to studying and managing plant and animal communities that include explicit considerations of community dynamics and biological and economic trade-offs.

Three Technical Approaches for Addressing Current and Future Challenges from Weeds

At present and increasingly in the future, the challenges and constraints associated with weed management are formidable: environmental damage caused by control practices, weed resistance to herbicides with little or no development of new herbicide chemistries, loss of herbicide active ingredients due to regulation, unintended dispersal of invasive species through increasingly globalized trade, more problematic infestations due to climate and land uses changes, and greater societal demands for both increased food production and enhanced protection of environmental quality. Here, we examine three technical approaches for improving weed management strategies to better address these challenges. We consider these as case studies illustrative of how insights into ecological and evolutionary patterns and processes can form the foundation of future weed management efforts; we do not suggest that our examples constitute an exclusive list of options.

Case 1: replacing heavy reliance on herbicides with integrated strategies employing diverse sets of complementary tactics

Almost six decades ago, Stern et al. (1959) described the importance of integrating multiple, complementary tactics to manage insect pests while reducing reliance on synthetic pesticides. Swanton and Wiese (1991) articulated a similar approach for integrated weed management (IWM) on arable land to protect environmental quality. Diversification of weed management strategies is considered critical for managing herbicide resistance in weeds (Norsworthy et al. 2012); as Shaner (2014) emphasized, "…a diverse weed management program that combines multiple methods is the only system that will work for the long term." Opportunities and potential benefits of integrating mechanical, cultural, biological, and chemical tactics have also been noted for invasive plant management in non-arable habitats (DiTomaso 2000).

Here we present two examples that illustrate how the integration of multiple tactics can contribute to effective weed management with reduced reliance on herbicides. The first example involves weed management in a large-scale, long-term cropping system experiment in the United States Corn Belt (Davis et al. 2012). The experiment included a conventionally managed corn (*Zea mays*)–soybean (*Glycine max*) rotation and a more diverse corn–soybean–cereal/alfalfa–alfalfa (*Medicago sativa*) system receiving lower amounts of herbicides. Triticale (X *Triticosecale*) was the cereal crop in 2003–2005 and oat (*Avena sativa*) was used thereafter. Reductions in herbicide use in the more diverse system resulted from applying herbicides only in bands over corn and soybean rows, rather than broadcast spraying; using an inter-row cultivator in the unsprayed areas between corn and soybean rows; and using mowing and hay removal rather than herbicides to control weeds in cereal stubble and alfalfa. Empirical measurements of weed seed population densities in soil of the experiment plots over a 9-yr period indicated that they declined for both the simple corn–soybean system under conventional, full-herbicide-rate management and the more diverse four-crop system treated with less herbicide (Fig. 3; Davis et al. 2012). During the period of 2003–2011, the latter system

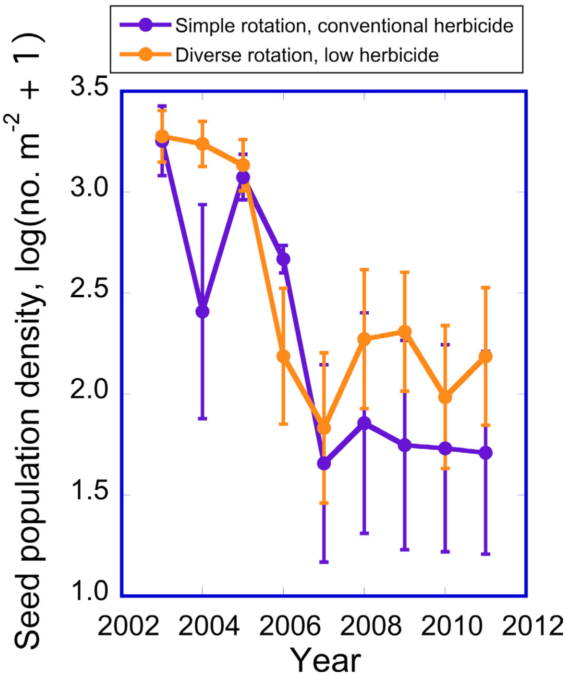

FIG. 3. Total viable weed seed population density to 20 cm depth in 2003–2011 in a simple corn-–soybean rotation and a more diverse corn–soybean–cereal/alfalfa–alfalfa rotation. Triticale was used as the cereal in 2003–2005 and oat was used thereafter. Corn and soybean in the simple system received full (standard) broadcast rates of herbicides, whereas banded applications of herbicides were applied to corn and soybean in the diverse system. No herbicides were applied to cereals or alfalfa. Data are redrawn from Davis et al. (2012); means and their standard errors are shown. Repeated measures analysis of variance indicated that the time effect was highly significant ($P < 0.0001$), whereas cropping system and time × cropping system effects were not significant ($P = 0.14$ and $P = 0.98$, respectively).

received 90% less herbicide (kg active ingredients per ha) and had up to 200-fold lower herbicide-related toxicity to freshwater organisms, as estimated by the USEtox model (Rosenbaum et al. 2008, Payet and Hugonnot 2014) (Davis et al. 2012). The more diverse system also matched or exceeded the crop yields and profitability of the simpler conventional system (Davis et al. 2012). Results of the study are consistent with those from a set of on-farm experiments conducted in Italy, Germany, and Slovenia, in which blending mechanical and chemical weed control tactics was found to be effective for suppressing weeds in corn with greatly reduced reliance on herbicides, while maintaining yields and economic returns (Vasileiadis et al. 2015). Importantly, modeling studies predict that more diverse management systems integrating chemical and non-chemical tactics can not only keep weed population densities lower, but also slow evolution of herbicide resistance (Renton et al. 2014).

A second example illustrating the effectiveness of integrating mechanical, cultural, biological, and chemical tactics involves suppression of the invasive woody species *Mimosa pigra* (Fig. 1D) in the Northern Territory, Australia. This species, native to the American tropics, forms dense, nearly monospecific thickets in Australia that reduce biodiversity, harbor feral animals, compete with pasture vegetation, and hinder livestock movement and access to water (Paynter and Flanagan 2004). Modeling analyses conducted by Buckley et al. (2004) indicated that the most successful strategy for suppressing *M. pigra* would involve a combination of herbicide application, mechanical control (crushing with a bulldozer), burning, and a reduction of small-scale disturbances; use of insect biological control agents would further improve the strategy. These predictions were corroborated with data from a 128-ha, multi-year field experiment reported by Paynter and Flanagan (2004), who concluded that herbicide, bulldozing, and fire used separately were not effective, but that combinations of tactics "cleared mimosa thickets and promoted establishment of competing vegetation that inhibited mimosa regeneration from seed." The abundance of one of five insect biological control agents investigated in the study was decreased by fire, but the other agents were either unaffected or increased by herbicide application, bulldozing, and fire, and were expected to contribute to mimosa suppression over the long term. Similarly, another modeling study showed that a combination of fire and cutting was more effective in suppressing native invasive species and protecting biodiversity than the same actions applied in isolation (Shackelford et al. 2013).

Integrated and diversified weed management is not a new idea, but its broad implementation remains challenging in many systems due to economic and social factors, as well its inherent site-specificity, complexity, and knowledge-intensity (Bastiaans et al. 2008). Moreover, while results of empirical experiments and modeling studies suggest that IWM strategies can be successful at the farm or micro-economic scale, it is not yet clear how such systems would work on regional and national scales if they involve diversification of cropping systems and integration of livestock production, with attendant shifts in supply and demand relationships and possible changes in farm revenue. These issues need to be addressed in future research.

Case 2: breeding and selecting weed-suppressive crops

Resistance to herbicides, primarily to glyphosate, is the dominant transgenic trait introduced into soybean, corn, cotton, canola, and sugar beet, with more than 100 million ha of herbicide-resistant genotypes of those crops grown worldwide in 2014 (James 2014). As glyphosate-resistant weeds have become more widespread and problematic, there has been a concomitant effort by the seed and chemical industry to develop transgenic crops with stacked resistances to glyphosate and other herbicides, including 2,4-D and dicamba (Mortensen et al. 2012).

For the United States, use of such stacked resistances is anticipated to more than double the total amount of herbicide active ingredients applied to crops such as soybean, with concomitant increases in damage to susceptible crops and non-target vegetation due to a greater mass of chemicals with high biological activity moving off-site (Mortensen et al. 2012). As noted previously, populations of a number of weed species have already exhibited resistance to more than one herbicide mode of action, including all of the chemistries currently being developed for the next generation of herbicide-resistant crops. Thus, stacked herbicide resistance in crops may retard the evolution of herbicide resistance in weeds, but is unlikely to stop it (Mortensen et al. 2012, Ervin and Jussaume 2014). Concerns over expanded reliance on herbicide-resistant cultivars and their partner herbicides are particularly acute for crops with co-occurring inter-fertile weedy relatives. In such cases, transfer of herbicide resistance genes from crops to weeds via pollen movement is likely, if not inevitable; examples include oilseed rape (*Brassica napus*) and weedy *Brassica rapa* populations (Warwick et al. 2008), cultivated and weedy red rice (*Oryza sativa*) (Shivrain et al. 2009), cultivated and wild sunflower (*Helianthus annuus*) (Burke et al. 2002), and wheat (*Triticum aestivum*) and jointed goatgrass (*Aegilops cylindrica*) (Seefeldt et al. 1998).

A desirable alternative or complement to engineering crops for herbicide resistance and then facing problems with environmental contamination and evolution of resistance would be to breed and select for weed-suppressive crop genotypes. There are already extensive data showing that different crop species and existing crop varieties vary considerably in their ability to suppress weeds (e.g., Worthington and Reberg-Horton 2013, Andrew et al. 2015). Competitive ability against weeds can be conferred by a number of heritable traits including tall shoots, rapid early growth, greater numbers of tillers and branches, and canopy architectures that provide greater ability to compete for light and shade neighbors, as well as differences in size and depth of root systems that affect access to water and nutrients (Lemerle et al. 1996, Olesen et al. 2004, Andrew et al. 2015). In addition, interactions between crops and weeds can be mediated by reductions in the ratio of red to far-red wavelengths in light due to absorption patterns by leaf pigments (Page et al. 2010), with considerable variability among genotypes of crops such as wheat and rice in their sensitivity to light quality and in the red/far-red ratios of light transmitted through their canopies (Merotto et al. 2009).

In the past, it was generally assumed that crop genotypes that are best able to suppress associated weeds have lower yield potential, since they typically allocate a greater proportion of biomass to non-harvestable parts (e.g., longer stems and bigger leaves with which to shade neighbors), rather than to harvested seeds or fruits. However, as noted by Weiner et al. (2010), it is the performance of the crop population, not the individual crop plant, that is important for both yield and weed suppression. Therefore, by using crop genotypes that tolerate high densities of conspecifics, crops could be planted at high densities (Lemerle et al. 2004) and in spatial arrangements that favor usurping resources from weeds more effectively, while maintaining or increasing crop yields. Though manipulations of crop density and arrangement cannot be assumed to be universally effective for weed suppression, results from recent experiments indicate the approach has significant potential value. Sowing wheat at high densities in a grid pattern rather than at lower density and in rows resulted in 65% less weed biomass and 60% greater yield relative to a standard lower-density, rowed sowing pattern (Weiner et al. 2010). For corn, high density, grid arrangements resulted in an average of 65% less weed biomass and 46% greater yield relative to a standard lower-density, rowed arrangement (Marín and Weiner 2014). In both experiments, significant differences were noted among genotypes in weed suppression ability and density responses, implying that opportunities exist for improving varieties for superior performance at high density.

Elevating population density is not appropriate for all crops, especially vegetables for which crowding decreases the size of harvestable units, affecting their market value. Changing planting arrangement may also require investment into modified machinery, making the initial outlay expensive, and planting in narrow rows may negate opportunities for inter-row cultivation. Increased seeding rates will involve increased cost. Economic and engineering analyses of these options are therefore needed.

A complementary approach to breeding for increased crop competitive ability involves breeding for increased allelopathic ability, i.e., an enhanced capacity to interfere with weed germination, growth, and development via chemicals exuded from crop roots or shoots. Genotypes of rice, wheat, barley (*Hordeum vulgare*), oat, rye (*Secale cereale*), and sorghum (*Sorghum bicolor*) have been identified with high allelopathic activity against weeds and efforts have been initiated to breed high-yielding, weed-suppressive cultivars through traditional techniques, quantitative trait locus (QTL) mapping, and marker assisted selection (Belz 2007).

Selection of crop genotypes for both competitive ability against weeds and increased allelopathic ability is possible and is being pursued in research programs for a number of cereal crops. Weed-suppressive rice cultivars that make use of allelopathic exudates and enhanced ability to compete for resources are now commercially available in the United States and China, and weed-suppressive wheat and barley cultivars are being bred for commercial release in Sweden (Worthington and Reberg-Horton 2013). A constraint is that breeders give much higher priority to other traits, such as disease resistance and suitability of grains for their end-use. In some cases, however, priorities overlap and traits selected for one reason can lead to other desirable effects. For example, increasing coleoptile length in wheat to allow the crop to be sown deeper for greater drought tolerance can result in better safety from pre-emergence herbicides and from seed predators, as well as in early vigor that will improve both water use efficiency and competitiveness with weeds (Amram et al. 2015). The best approach in the short term may be to focus on such multi-advantage traits rather than simply on weed suppression.

Commercial development of allelopathic crops may not be required for on-farm implementation in cases where crop species with allelopathic characteristics are already available through informal networks. A particularly striking example of this can be seen in the development of new strategies for managing the parasitic weed *Striga hermonthica* through use of the legume *Desmodium uncinatum,* which is being distributed in local markets and intercropped with corn, sorghum, and millet in East Africa (Khan et al. 2008). The weed species can have devastating effects on grain production, particularly in fields with nutrient-depleted soils. Root exudates of the *D. uncinatum* stimulate germination of the weed and then inhibit its subsequent development, thus preventing normal attachment to crop roots. In an 8-yr field experiment, intercropping corn with *D. uncinatum* led to near complete elimination of *S. hermonthicum* seeds in the soil, whereas seed population densities of the weed tripled in fields cropped with monoculture corn (Khan et al. 2008). In addition to suppressing this particularly problematic weed, the legume provides fodder for livestock and nitrogen to bolster the growth of associated grain crops, increasing grain yields. Testing of the corn–*D. uncinatum* intercropping approach on 395 farms in Kenya, Uganda, and Tanzania corroborated results from on-station experiments: *S. hermonthica* population densities were 18 times lower and corn yields were 2.5 times greater in the intercrop than in corn monocultures (Midega et al. 2015). Midega et al. (2015) reported that about 35000 smallholder farmers in drier areas of western Kenya, eastern Uganda, the Lake Victoria basin of Tanzania, and northern Ethiopia have adopted the approach.

Allelochemical suppression is not without certain limitations. Allelochemicals can have differential effects on receptor species, with much of this variation explained by differences in seed size: small-seeded species are more susceptible to allelochemicals than are larger-seeded species (Liebman and Davis 2000). Thus, large-seeded weeds might be relatively immune to the effects of allelochemicals. Perennial weed species, whose shoots re-grow from relatively large perennating structures, are unlikely to be strongly affected by allelochemicals. Olofsdotter et al. (2002) found that autotoxicity was generally not a problem for rice varieties with high allelopathic potential; whether this is true for other allelopathic crop species remains to be investigated.

Case 3: managing weeds in a site-specific manner using advanced sensing technologies and knowledge of ecological patterns and processes

Weeds often are not distributed evenly within fields (Rew and Cousens 2001, Heijting et al. 2007) or across landscapes (Pollnac et al. 2012). Instead, they tend to occur in patches of varying size, shape and density. Fig. 4 depicts the spatio-temporal dynamics of two weeds, *Alopecurus myosuroides* and *Chenopodium album*, in a conventionally managed arable farm in East Anglia, UK; considerable heterogeneity is apparent at both within- and among-field scales. Patchiness in weed distributions reflects differences in crop rotations and local management decisions. It may also indicate the arrival of new colonists, failures of control

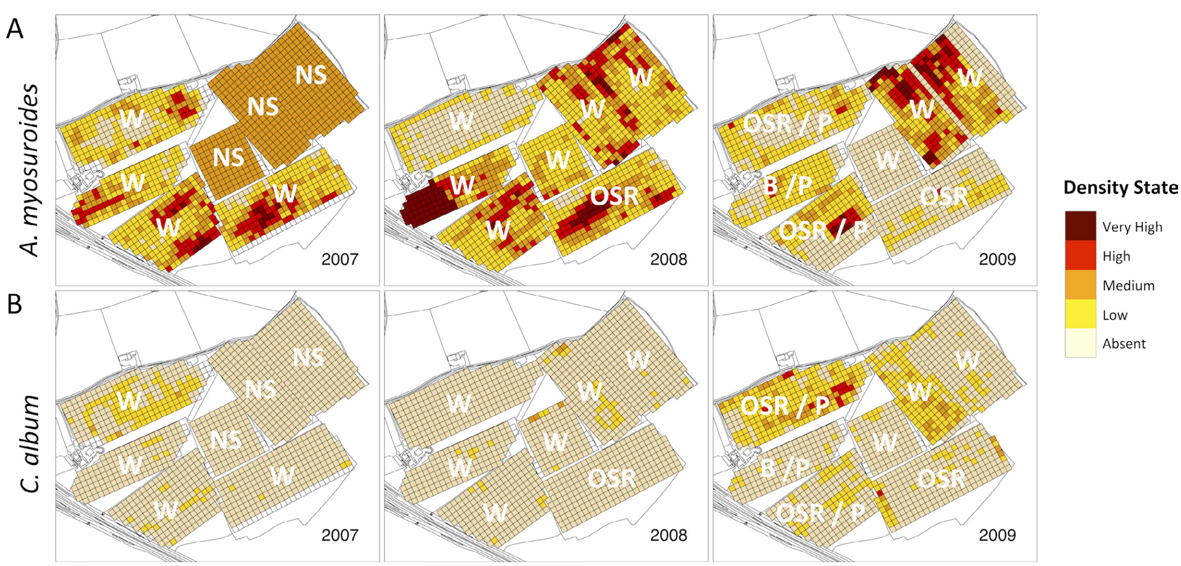

FIG. 4. Patch dynamics of the weeds (A) *Alopecurus myosuroides* and (B) *Chenopodium album* within seven fields belonging to a conventionally managed arable farm in East Anglia, UK. Density-structured data were collected in 2007, 2008, and 2009; each field was divided into a contiguous lattice of 20 × 20 m subplots, and subplots were assigned one of five density states each year. Density states of the two weeds are not directly comparable. Data were collected by a small team of trained observers over the course of a single day. Crops present were wheat (W), oilseed rape (OSR), barley (B), and peas (P). NS denotes a non-surveyed field. See Queenborough et al. (2011) for details.

practices and crop competition to suppress already established weed populations, or dispersal patterns of weed propagules moved by gravity, farm machinery, animals, wind, and other vectors. Once established, weed patches may grow or shrink in size over time due to weather conditions, grazing regimes, soil disturbances, direct control practices like cultivation or herbicide spraying, and other factors (Humston et al. 2005).

Many non-arable management areas are sufficiently large that complete surveys on the ground to locate weeds are not feasible, thus increasing probabilities of successful establishment by new colonists and spread of existing populations. Remote sensing from satellites and unmanned aircraft systems (UAS) and the use of geographic information systems (GIS) offer important opportunities to detect and map recently established populations of invasive plants in rangeland and natural areas before substantial patch expansions occur (Rew et al. 2005, Shaw 2005). Additionally, knowledge of site-specific environmental factors that affect invasive plant distributions can be used to develop probability of occurrence maps and to guide management efforts. For example, Pollnac et al. (2012) examined environmental variables affecting the distributions of 34 nonnative plant species within the Greater Yellowstone Ecosystem (USA) and found that the probability of occurrence of many of the common species was negatively correlated with elevation and distance to roads, and positively correlated with disturbance intensity (e.g., grazing, logging). Once such ecological relationships are validated, maps of predicted distributions can then be used to guide on-the-ground surveys, identify vulnerable areas in need of protection, focus management efforts to better target invasive species, and further improve habitat suitability models (Rew et al. 2005, Stohlgren and Schnase 2006, Thuiller et al. 2006, Crall et al. 2013).

In the case of arable weeds, for which control tactics like herbicides generally are applied uniformly to whole fields, production costs and risks of environmental contamination might be decreased if weeds were treated only when and where they are present (Shaw 2005, Christensen et al. 2009). Consequently, improved detection and site-specific weed treatment technologies that take into account weed species identities, population densities, stage of development, and potential economic effects on crop yield are highly desirable.

Recent technical advances have brought such improvements closer to broad-scale implementation. Cameras or sensors can be mounted on a tractor, sprayer, or implement (Christensen et al. 2009), or on a UAS (Rasmussen et al. 2013) to identify weeds and trigger a local herbicide application, or on mechanical implements that cut or dislodge weeds when they are encountered (Tillet and Hague 2006, Christensen et al. 2009). Detection of separate weed taxa (e.g., dicotyledonous vs. monocotyledonous species) coupled with differential application of taxon-specific herbicides has the potential for further lowering herbicide use (Gutjahr et al. 2012). Gerhards and Oebel (2006) conducted on-farm weed control experiments using technologies for digital image analysis, computer-based decision making, and global positioning system-controlled patch spraying and obtained 6–81% reductions in herbicide use in wheat, barley, corn, sugar beet (*Beta vulgaris*), and rapeseed, while maintaining levels of weed control similar to full-field, broadcast spraying. Auto-guidance systems are now being developed for high-speed cultivators with centimeter accuracy, making timely cultivation of large fields more feasible (Heidman et al. 2002, López-Granados 2011). Location and mechanical destruction of the perennial grassland weed *Rumex obtusifolius* by a prototypic self-propelled robot was achieved in on-farm trials using a unit equipped with an image analysis system and a vertical rod that cut the weed when it was encountered; 93% of *R. obtusifolius* plants present in a pasture were detected and 75% of the individual plants cut by the machine did not regrow (Van Evert et al. 2011). Recently, an estimation of plant growth parameters via image-based reconstruction of their three-dimensional shape was developed (Lati et al. 2013). This three-dimensional model allows the estimation of weed biomass from UAS.

Despite these advances in both chemical and physical approaches to site-specific weed management, economic analyses are still needed to determine how little a system would need to cost before a farmer was prepared to invest in it. Such information would give targets for engineers. There are also practical issues that may need to be solved. For example, the use of a conventional boom sprayer for site-specific management may mean that the farmer does not know how much herbicide solution to prepare, which risks both wastage and disposal problems; site-specific spraying may therefore require the coincident development of direct injection systems that do not require pre-mixing of herbicide with water. Information is also needed concerning the performance of site-specific technologies under varying weather conditions, so as to provide better assessments of risks of failure and probabilities of success.

Although much of the focus in site-specific weed management has been on technological innovations, ecologists also have much to contribute to improvements in site-specific strategies. Of particular importance are experiments and modeling analyses that foster the identification of weed life-history stages that have a high degree of influence on population growth rates and that are especially vulnerable to site-specific management interventions (McEvoy and Coombs 1999, Davis 2006). Understanding what drives weed patches toward expansion or local extinction is a critical intersection between ecology and weed management (Mohler 2001). Empirically derived predictive modeling tools that leverage "coarse," easily collected ecological data are needed. For example, density-structured population models (Freckleton et al. 2011) project changes among a small set of discrete density states (e.g., those represented in Fig. 4). These are much simpler to parameterize than

Fig. 5. A "seed destructor" attached to the back end of a combine harvester in an Australian grain field. The machine grinds and destroys weed seeds contained in crop residue passing through the combine. Photo courtesy of J. Millhouse.

traditional population models, and facilitate rapid data collection by substituting coarse density assessments for fully enumerated population densities. The development of small-scale remote sensing platforms, such as UAS, has potential to facilitate the use of such models to guide management decisions.

An example of how ecology and farm technology might be melded for improved weed management can be seen in the development of "mechanical seed predators" that mimic the impacts of insects, rodents, birds, and other animals that consume weed seeds. Seed survival is a critical factor affecting the population growth rates of annual weed species (Davis 2006), and patch expansion within fields is often a function of seed dispersal by crop harvesting equipment (Mohler 2001). Consequently, special machinery has been developed that trails behind a combine harvester to trap and grind weed seeds picked up during crop harvesting (Fig. 5; Walsh et al. 2012). Walsh et al. (2012) reported that such machinery would destroy 95% of *Lolium rigidum*, *Avena* spp., *Bromus rigidus*, and *Raphanus raphanistrum* seeds present in the chaff fraction of wheat harvest residues. In on-farm tests conducted in Western Australia in which crop fields were treated with herbicides, use of a seed destruction device reduced infestations of *L. rigidum* from 35 to 50 plants/m^2 to <1 plant/m^2 over a 10-yr period; in contrast, where herbicides alone were used, *L. rigidum* densities remained above 4 plant/m^2 (Walsh et al. 2013). New mechanical designs are now being explored to place seed grinders directly within combine harvesters and increase harvesting speeds.

Pathways Toward Adoption and Implementation of Improved Weed Management Strategies

A notable characteristic of the three described approaches for improving weed management is that each was suggested in at least rudimentary form two or more decades ago (see, e.g., Walker and Buchanan 1982, Mortensen et al. 1995). Though a wealth of details about each approach has been elucidated in the ensuing years, in most regions of the world broad-scale use of these and other integrated weed management approaches has never occurred. Owen et al. (2014) assessed the status of integrated weed management in the United States and Canada and concluded that, "in spite of compelling information," there has been only limited adoption of strategies employing diverse sets of tactics in both countries. In France, where a 10-yr national program was begun in 2008 to enhance adoption and implementation of integrated pest management and to reduce pesticide use by 50%, targets are not being reached; only 4% of agricultural land is currently managed with organic or integrated pest management techniques (Chantre and Cardona 2014).

The factors responsible for the failure to move effectively from science to practice with regard to integrated weed management are many and diverse, but include: (1) insufficient and/or inappropriate government policy instruments to alter farmer and land manager behavior; (2) a lack of market mechanisms to motivate farmers to change their crop protection practices; (3) a paucity of social infrastructure with which to support relevant learning and decision-making by farmers and land managers; and (4) the different lifestyles and values of land owners and managers that lead them to favor particular management systems and to differ in attitudes to adopt change (Mohler et al. 2001, Jordan et al. 2006, Pannell et al. 2011). Here we examine a number of ways those constraints might be overcome. We recognize that agriculture and land management are complex, adaptive systems that contain much heterogeneity among the members of a given class or system component (Institute of Medicine and National Research Council 2015). Consequently, no single strategy for promoting change will be universally useful or appropriate. Nonetheless, we believe it important to recognize the range of options available.

Government policy

Economic considerations play a major role in farmer and land manager decisions related to weed management. In general, most farmers and land managers opt for practices that are economically advantageous in the short term. Consequently, ecologically based weed management strategies that are site-specific and complex, and that may forego some immediate profits in pursuit of environmental protection and other social benefits can be unattractive without subsidies or other economic incentives. An example of this situation is the so-called cross-compliance subsidy in the Netherlands (Van Zeeland et al. 2009). Farmers were rewarded when they replaced herbicide sprays in corn with mechanical control tactics and used herbicides with reduced impacts on the environment. However, after termination of the arrangement, herbicide use increased 20% and use of cheaper and less environmentally friendly herbicides also increased. Thus, long-term mechanisms for generating funds and maintaining payments to farmers would likely be necessary if public subsidy and cost-sharing programs were the basis for sustained changes in weed management practices.

Taxes on herbicide sales are a possible means of generating revenue to foster changes in weed management. In Denmark, pesticide use, including herbicide use, has been regulated since 1986 through a series of three political action plans. One of the regulation instruments in each plan has been charges on pesticides. The first set of policies enacted was intended to halve the quantity of pesticide active ingredients (a.i.) applied between a baseline of 1981–1985 and 1997 (Gianessi et al. 2009). Although this was achieved, in the case of weed management almost all of the reduction in herbicide load was effected by a switch from heavy reliance on phenoxy herbicides to greater reliance on sulfonylurea herbicides, which are applied at lower rates (kg a.i. per ha) (Gianessi et al. 2009). A negative consequence of the move to sulfonylurea herbicides is that they select for herbicide resistance more rapidly than most other chemicals. Additionally, the frequency of herbicide treatments (number of full dose applications·ha^{-1}·yr^{-1}) actually increased between 2000 and 2011 (Danish Ministry of the Environment 2012).

The latest 3-yr plan, set in motion in 2011, sought to reduce pesticide loads on the environment and impacts on human health by 40% through shifts in products applied and reductions in treatment frequencies (Danish Ministry of the Environment 2012). Included within the plan were differential surcharges placed on pesticides based on human and ecological toxicity estimates for individual products. These charges were intended to discourage the use of high-risk products and were expected to generate €34 million in revenue over a 3-yr period on top of the basic charges on pesticides. The additional revenue was targeted to fund research and technology relevant to the management of weeds and other pests; better teaching and information delivery for users of pesticides and the general public concerning risks of pesticide use; education for farmers and their advisors on how to reduce pesticide use and how to choose pesticides causing the least environmental damage; and increased inspections of farms by government personnel to check spraying equipment and application records (Danish Ministry of the Environment 2012). In addition, the plan called for imposition of stricter approval processes for new pesticides and reregistration of existing pesticides, and stricter penalties for illegal imports and illegal uses of pesticides.

The Danish plan won broad political support, including from opposition parties (Danish Ministry of the Environment 2012), but some analysts noted that it might have contained elements leading to unintended effects, e.g., by limiting choices of pesticides to those with a narrow range of sites of action, risks of resistance evolution might increase (ENDURE Network 2013). Additionally, there were concerns that through regulatory withdrawal of many pesticides from the marketplace and higher taxes on remaining products, farmers might be left without viable chemical options for controlling pests (ENDURE Network 2013). Evaluation of the impacts of the Danish policies should provide insights into the effects of tax instruments and other mandated approaches.

Market-related actions of agricultural processors and retailers

In industrialized countries and a rising number of developing countries, agricultural value chains comprise input suppliers (for seeds, fertilizers, pesticides, machinery, etc.), farms and ranches, processing and retailing firms, and consumers (Institute of Medicine and National Research Council 2015). In the United States, of the US$1.6 trillion spent annually on food by consumers, ~63% accrues to the processing and retail sales sector. Consequently, large-scale processors and retailers within the agricultural value chain have substantial financial resources and control with which to effect changes in production practices used by farmers supplying crop and livestock commodities. For example, responding to consumer demand, Perdue Farms, Walmart, and Tyson Foods now offer chicken, beef, and pork raised without antibiotics, as well as conventional products raised with antibiotics (Kesmodel et al. 2014). McDonalds announced in 2015 that it would shift to using eggs from cage-free hens; Burger King, Sara Lee, Unilever, and General Mills also are expected to follow this initiative (Strom 2015). A number of large-scale firms in the processing and retail sectors are now considering implementing standards for on-farm crop management to improve environmental impacts and increase sustainability (Gullickson 2015). Although the potential impacts of these changes are not yet determined, the magnitude of sales by these firms is such that significant amounts of production could be affected.

The impacts of market-related actions of agricultural processors and retailers on weed management can be seen in an example from England, where 35000 Mg of peas are marketed annually by Birds Eye, a subsidiary of Unilever. Based on a supply chain program initiated in 1998, Unilever has worked with the farmers that supply it with peas to better control weeds through crop rotation, careful seedbed preparation, weed mapping for targeted herbicide application, hand-weeding patches of new weed species, and choice of herbicide products and rates based on efficacy and safety (Williamson and Buffin 2005). The company also conducts research and provides technical assistance to growers. Its weed management protocols are part of a broader effort to reduce pesticide use; over the previous 20 yr, pesticide application (kg a.i. per ha) has been halved (Williamson and Buffin 2005).

Learning and decision-making by farmers and land managers

Government policies and market activities may set the context for weed management practices, but farmers and land managers are ultimately responsible for implementing them. Consequently, focusing on learning and decision-making by farmers and land managers is critically important for effecting changes in weed management practices.

Key decisions by farmers and land managers are shaped not just by scientific information, but also by previous experience, familiarity with different technologies, interactions with peers and advisors, and labor requirements, economic returns, and perceived risks of different management options (Staver 2001, Meir and Williamson 2005). In surveys conducted in the Midwestern United States, 78% of conventional farmers reported that they looked first to agrichemical salespeople for weed management information (Arbuckle 2014), whereas 83% of organic farmers reported that they relied most heavily on other farmers for weed management information (DeDecker et al. 2014). Farmers in two regions of northern France were found to make extensive use of information from both public and private advisory services, as well from other farmers (Chantre and Cardona 2014). Relevant information may also pass through social and professional networks (Ervin and Jussaume 2014). For example, although Arbuckle (2014) and DeDecker et al. (2014) reported that there were relatively few direct links between Midwestern United States farmers and public extension service personnel, the agrichemical retailers and private sector advisors from whom farmers obtained pest management recommendations were found to use and rely on information from university personnel delivered through newsletters, electronic media, field days, conferences, and consultations (Wintersteen et al. 1999). Thus, in many cases, education efforts for farmers are being focused most effectively on their advisors (Chantre and Cardona 2014, Kragt and Llewellyn 2014). With regard to farmers' and land managers' preferences for factors promoting change in management practices, landholders in Victoria, Australia, indicated strongest support for voluntary programs encouraging communication and participation by stakeholders, as well as for education; market-based instruments and command-and control regulation were viewed much less favorably (Cocklin et al. 2007).

Scientists and extension personnel typically approach education and outreach activities meant to enhance farmer and land manager learning and decision-making in two distinct ways. The first is to fill perceived voids in understanding and knowledge by developing relevant information and accessible "messages"; the second is to focus on ways to enhance the process of learning rather than the receipt of facts, especially through participation in collaborative learning groups (Meir and Williamson 2005, Jordan et al. 2006).

With regard to the first path, the "filling information deficits" model, a substantial case can be made that scientific information is being generated that is directly relevant for managing current and future challenges that farmers face from weeds. In particular, recent theoretical and practical research has focused on strategies for managing herbicide resistant weeds on conventional farms and weed seedbanks on organic farms, which are critical topics for the respective types of farming (Riemens et al. 2010, García et al. 2014, Jabbour et al. 2014, Renton et al. 2014). Communicating such information effectively may be contingent on linking it to messages that trigger changes in perception and behavior. For example, Llewellyn et al. (2007) found that among grain farmers in Western Australia, adoption of a diverse set of integrated weed management practices was more likely for those farmers already coping with herbicide-resistant weeds and for those who did not expect that new herbicides would become rapidly available. Thus, communicating narratives that include representative farmers dealing with herbicide-resistant weeds and emphasizing the paucity of new chemical options is especially useful for motivating changes in weed management by a broader set of farmers. It is also important to recognize that most farmers are more comfortable making incremental changes than implementing a whole set of practices at one time (Nazarko et al. 2005, Llewellyn et al. 2007, Chantre and Cardona 2014). Consequently, it may be more effective to communicate desired components of integrated weed management strategies as an incremental series of relatively small changes rather than deliver them as a single large package.

With regard to the second path, the "learning" model, we suggest several complementary approaches might prove useful in promoting the adoption and implementation of improved weed management strategies: (1) formation of "field schools" for joint learning and discussion among researchers, extension personnel, farmers, land managers, and others; (2) investigation of new (and potentially unsuccessful) approaches at farm and landscape scales by cooperative groups of farmers, land managers, and researchers; and (3) development of demonstration and outreach sites on farms and management areas that have implemented new weed management strategies successfully.

Enhanced learning through "farmer field schools" has been successful for the development and implementation of integrated insect pest management strategies for rice in Southeast Asia (Röling and van de Fliert 1998). In Indonesia, field schools operated with the premise that farmers are fully capable of observation, experimentation, planning, joint deliberation, and careful decision-making, but need assistance in understanding the biology and functional roles of different pests and natural enemies, and the full consequences of various management tactics, including insecticide application (Kenmore 1996). Accordingly, special field activities (e.g., visits to "insect zoos") were conducted to help farmers observe the impacts of natural enemies on rice insect pests and to promote decision-making skills (Ooi 1996, Röling and van de Fliert 1998). Insecticide use decreased 60% and rice production increased 15% for Indonesian farmers participating in field schools compared with non-participating farmers (Conway 2012). Similar achievements in reducing insecticide use and maintaining or increasing yields and profitability have been realized with field schools in other countries and with other crops (Van den Berg and Jiggins 2007, Settle et al. 2014). As of 2011, farmer field schools had been initiated in 78 countries with four million graduates (Ekström and Ekbom 2011).

Collaborative learning through on-farm experimentation with new methods for weed management may provide insights into the strengths and shortcomings of different methods under "real world" conditions. Nazarko et al. (2003) summarized a pilot project that was conducted for several years in Manitoba, Canada, by a group of 71 farmers working with extension workers and university and government researchers. The project was initiated in response to low commodity prices, rising production costs, and a desire to reduce pesticide use, and involved 120 fields comprising 2850 ha. Crops included wheat, barley, oat, rye, flax (*Linum usitatissimum*), sunflower, canola, and alfalfa. Weeds were the dominant group of pests dealt with by the farmers, with ~80% of total pesticide costs in the region spent on herbicides. Farmers in the project compared conventional weed management strategies against sets of tactics that included increased seeding rates, delayed seeding dates, choice of competitive crops and varieties, and sequencing forage crops such as alfalfa before cereals; herbicides could be used to control weeds before sowing crops, but none were applied after sowing. Fields treated with alternative approaches had weed densities that were 29% lower than in fields under conventional management (before in-crop herbicides were applied), although this result may have reflected farmers' choice of less weedy fields for the alternative tactics (Nazarko et al. 2003). The project was not continued and the particular combinations of tactics that were successful were not elucidated, but Nazarko et al. (2003) noted that the participatory approach used in the study was useful in assessing the implementation of alternative production practices at farm scale and constituted a valuable learning opportunity for the researchers involved.

Farmer and land manager learning and decision-making with regard to weed management may also be supported through networks of "pilot farms" (Vereijken 1997) or "lighthouse farms" (Nicholls et al. 2004), and analogous types of non-arable land management sites. Pilot and lighthouse farms are commercial operations where operators host visits by other farmers and provide information and demonstrations of innovative techniques and strategies that have proven successful. Such farmers may work with researchers in adapting techniques developed in research station plots, or allow researchers to make measurements on the farm to quantify various performance indicators (Vereijken 1997). Through the development of a spatially dispersed network of such farms, other farmers have access to sources of information in their neighborhood and can observe the performance of strategies on a whole-farm scale rarely addressed in research station experiments. On-farm research and demonstration networks also have been used to enhance learning about weed management in California, USA and Central America (Staver 2001). Harp (1996) described a network of pilot farms in Iowa, USA, facilitated by the non-governmental organization Practical Farmers of Iowa and university researchers and students in which farmers conducted 78 weed control trials over an 8-yr period, including investigations of the effects of ridge tillage equipment, with and without herbicides, on weed densities, corn and soybean yields, and costs. Results of the latter experiments indicated that ridge tillage practices were efficacious whether or not herbicides were used. This information was distributed through field days, farmer-to-farmer discussions, meetings, and newsletters. The organization has continued to grow in staff and membership, with an emphasis on coordinated, cooperative on-farm experiments.

Although collaborative learning between farmers, land managers, researchers, and others is clearly a way to achieve desirable outcomes (Jordan et al. 2006), its facilitation on a broad scale is expensive. Over the past several decades, governments in developed countries have been reducing their extension efforts, regarding farming as a private-good investment that should be financed by industry. While externalities such as pollution of rivers and aquifers are still recognized as issues demanding the action of government, changes to farming systems to make them more sustainable are not. Hence, there is an important need to better link public policy outcomes with the achievement of on-the-ground actions.

Conclusions

Weed management is a critically important activity on both agricultural and non-agricultural lands, but it faces increasing challenges related to environmental damage caused by control practices, weed resistance to herbicides, accelerated rates of weed dispersal through trade activities, and greater weed impacts due to changes in climate and land use. Broad-scale use of new approaches is needed if weed management is to be successful in the coming era.

A considerable amount of research indicates that weed management would be improved by replacing heavy reliance on herbicides with integrated strategies employing diverse sets of tactics; breeding weed-suppressive crop genotypes; and expanding efforts to manage weeds in a site-specific manner using advanced sensing technologies and knowledge of ecological patterns and processes. Impediments to employing these and other alternative approaches include a lack of appropriate government policy instruments to selectively reward and discourage management practices, insufficient market mechanisms to encourage changes in farmer and land manager behavior, and a paucity of social infrastructure with which to support relevant learning and decision-making by farmers and land managers. There is no clear formula with which to determine which sets of government funded incentives, regulations, taxes, industry liaisons, educational campaigns, and learning networks will be effective in various locations. Nonetheless, because farmers and land managers are ultimately responsible for implementing weed management practices, special attention to their perceptions, goals, and decision-making processes seems warranted. In some cases, directing educational efforts at the public and private sector advisors working directly with farmers and land managers may be the most cost- and time-effective manner of delivering scientific information to its end users. Additionally, accessible research and demonstration sites operating at farm and landscape scales may serve to promote learning by farmers and land managers about alternative weed management strategies.

If diversified management strategies, weed-suppressive crop genotypes, and innovative sensing and treatment technologies could be developed so as to be inexpensive and reliably consistent on research stations, farmer field schools and pilot farms may provide venues to accelerate their adoption. A complementary approach would be to explicitly develop and maintain national and local policies and commercial relationships that affect farm production costs and product values through environmental regulations, enhanced market opportunities, outreach and education activities, and incentive payments. The net effect would be the formation of levers to influence decisions concerning weed management (Williamson and Buffin 2005, Mortensen et al. 2012).

The potential benefits of improving weed management with strategies based on ecological and evolutionary principles include better long-term protection of food production capacity and farm profitability; less damage to non-target species, water, and other resources; greater integrity of plant and animal communities in non-agricultural areas; and maintenance of weed susceptibility to control practices (i.e., herbicide resistance prevention). Achieving these benefits will require multidisciplinary teams comprised of scientists, engineers, economists, sociologists, educators, farmers, land managers, industry personnel, and others willing to focus on weeds within whole farming systems and land management units.

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