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Late-Season Seed Production in Arable Weed Communities: Management Implications

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Late-season weed escapes are often ignored because they rarely cause crop yield penalty. Traditional weed management recommendations are based on the economic threshold (ET) approach, wherein management is required if the predicted current-season yield loss is greater than the cost of control interventions. While ET-based weed management can reduce current-season production costs and promote farmland biodiversity, it does not consider the long-term biological and economic consequences associated with late-season weed seed production. An important concern is that late-season weed seed production will replenish the soil seedbank, ensuring future weed problems. In the context of herbicide resistance evolution, allowing late-season weed seed production can be problematic because the probabilities of occurrence of resistant mutants rise with increases in seed production. A key component of herbicide resistance mitigation and management is preventing seed production and buildup of the soil seedbank. Late-season weed management efforts constitute additional expenses to growers, which cannot be recouped in that growing season, but any such investment must be weighed against the perceived long-term benefits. It appears that management of late-season weed escapes is valuable in a number of situations, and the degree to which management interventions should be employed can be case-specific. Adoption of economic optimum thresholds (EOTs), which can be established using bio-economic models, will be useful for making management decisions for late-season weed escapes. In systems vulnerable to herbicide resistance evolution, bio-economic resistance thresholds (BERTs) will be appropriate and bio-economic resistance models (BERMs) will be helpful for establishing such thresholds for specific production scenarios. Management considerations for late-season weed escapes are discussed, and knowledge gaps for future research are identified.

Key words: Bio-economic threshold, bio-economic resistance threshold, bio-economic models, farmland biodiversity, herbicide resistance, late-emerging cohorts, weed escapes.

Late-season weed escapes comprise weeds that survive early-season weed control interventions (i.e., early-season survivors) and weeds that escape control measures by emerging later in the crop after weed control measures have ceased (i.e., late-emerging weeds) or by emerging after the current crop has been harvested (i.e., postharvest recruits). The most common causes of early-season survivors include inadequate herbicide rate, poor spray coverage, absence of an adjuvant, application at inappropriate weed size, herbicide interactions, and unfavorable environmental conditions, leading to reduced weed control (Hartzler 2001; Jordan et al. 1997). Even when applications are made under ideal conditions and at an appropriate growth stage, weed control is rarely 100% over a vast production area and early-season survivors are typical in production fields (Van Acker and Bartlinski 2005). This is favored by a reduction in tillage, greater dependency on herbicides, and limited crop rotation (Carlson and Burnside 1981).

Many weed species exhibit a prolonged emergence pattern, with several cohorts emerging throughout the growing season (e.g., Jha and Norsworthy 2009). The ability of weeds to emerge for prolonged periods allows them to escape herbicide treatments (Johnson et al. 2004b), and delayed emergence is the main cause of weed escapes under herbicide programs limited to early-season applications (Hennen et al. 2002; Scursoni et al. 2007). Seed production is typically low in late-emerging weed cohorts in cropped situations (Bagavathiannan et al. 2011c; Bosnic and Swanton 1997b; Steckel and Sprague 2004) because late-emerging seedlings are affected by crop competition (Baumann et al. 2001; Zimdahl 2004). These effects are stronger in crops or production systems that provide rapid canopy closure (Mayen et al. 2008; Steckel and Sprague 2004). However, late-emerging weeds may occur at high densities (Scursoni et al. 2007), and some late-emerging individuals benefit from gaps in crop establishment or from slow crop growth caused by environmental conditions such as wet and cool weather; weeds are known to exhibit plastic yield characteristics (Grime 1979). Additionally, weeds that emerge after crop harvest and/or those that survive harvest operation can continue to grow and contribute to the soil seedbank (Young and Whitesides 1987; Young et al. 2008). In temperate regions, postharvest recruits can be an issue if there is a sufficient time window between postharvest seedling emergence and first killing frost, whereas in warmer regions, seed production in postharvest recruits is possible under fallow situations.

Late-season weed escapes are prevalent in several crop production systems (e.g., Leeson et al. 2005), but they exert limited influence on crop yield (Zimdahl 2004). Traditional weed management approaches based on the ET and *critical weed-free period* concepts rarely warrant control of late-season escapes because they are unlikely to cause crop yield reduction (Baumann et al. 1993). However, the ET-based approach ignores the contribution of weed seed production to seedbank replenishment (Cousens and Mortimer 1995; Hartzler 1996), exacerbating problems in subsequent crops and increasing future weed management costs (Coble and Mortensen 1992; Mayen et al. 2008; Norsworthy and Oliver 2002). Walker and Oliver (2008) argued that effective long-term weed management strategies should aim to reduce late-season seed production in arable weed communities.

Late-season weed seed production has been gaining particular attention with the changing weed management paradigm as a result of herbicide-resistant weeds (Norsworthy et al. 2012). Herbicide resistance in arable weeds has been a relatively recent but growing issue in several crop production systems, which has forced us to revisit some of the traditional approaches to managing late-season weed escapes. It has been touted that preventing seed production by late-season weed

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escapes would help mitigate the evolution and spread of herbicide resistance because the key is to prevent the occurrence and perpetuation of rare resistant individuals (Jasieniuk et al. 1996; Norsworthy et al. 2012). Although a number of researchers have emphasized the importance of managing late-season weed escapes (e.g., Norris 1999; Walker and Oliver 2008), findings of some other researchers suggest that the benefits of not controlling subthreshold late-season weed escapes are at least twofold: (1) this approach reduces current-season weed management costs and reduces herbicide usage and associated concerns (Zimdahl 2004), and (2) late-season weed escapes may serve as vital food sources for arthropods, birds, and other herbivores (Gibbons et al. 2006; Holland et al. 2006) and facilitate *in situ* conservation of plant communities (Altieri and Merrick 1987), promoting farmland biodiversity and ultimately leading to improved agroecosystem functioning (Franke et al. 2009; Marshall et al. 2003).

It is not clear as to what extent managing late-season weed seed production is necessary, and it is an important question that warrants immediate attention. The objective of this review is to analyze the existing literature on late-season weed seed production and explore appropriate management considerations.

Significance of Late-Season Weed Escapes

Most farmers adopt weed management programs that are effective in controlling weeds and preventing weed seed production. Despite the continued efforts of farmers to control weeds, the problem persists; late-season escapes are a major contributor to seedbank persistence. A key biological characteristic of weeds that facilitate substantial escapes include emergence patterns that permit them to become too large at the time of POST applications or allow them to emerge after applications (Johnson et al. 2004b). For example, barnyardgrass [*Echinochloa crus-galli* (L.) Beauv] seedling emergence occurrs from April to early September in Arkansas (Bagavathiannan et al. 2011a), but weed control measures usually cease around mid-June in Arkansas row crop production systems. In Arkansas cotton (*Gossypium hirsutum* L.), barnyardgrass seedlings that emerge as late as 7 wk after crop emergence (around late June for cotton planted in early May) produced up to 1,500 seeds plant^{-1} (Bagavathiannan et al. 2011c). In New South Wales, Australia, Blackshaw et al. (2002) observed considerable seed production (about 1,000 seeds m^{-2}) of wild radish (*Raphanus raphanistrum* L.) when it emerged as late as 10 wk after canola [*Brassica napus* (L.) cv. Oscar]. Late-season weed escapes are characteristic of weed control programs consisting of total POST applications with nonresidual herbicides (VanGessel et al. 2001), which have been common in many production situations. In Indiana, Johnson et al. (2004a) conducted a survey of late-season weed escapes in soybean [*Glycine max* (L.) Merr.] fields and found that only about 3% of the surveyed fields (22 out of 718) had no weed escapes present. In western Canada, weed surveys conducted across the Prairie Provinces revealed that late-season weed escapes are prevalent in crop production fields (Leeson et al. 2005).

Weed escapes constitute the largest source of seed input to the soil seedbank (Cavers 1983). For many weed species, a few escapes would be sufficient to ensure seedbank renewal because of their prolific seed production, although the level of seed production is affected by the time of weed emergence relative to the crop (Bosnic and Swanton 1997b; Steckel and Sprague 2004). A meager escape of 12 female Palmer amaranth (*Amaranthus palmeri* S. Wats.) plants ha^{-1} may result in a seedbank addition of about 5 million seeds ha^{-1} (Culpepper and Sosnoskie 2011). A ground cover of 0.1% by common lambsquarters (*Chenopodium album* L.) escapes produced about 500 seeds m^{-2} in glyphosate-resistant soybean (Scursoni et al. 2007). Such levels may be significant for seedbank replenishment, and studies have demonstrated that the residual seedbank population may be sufficient to ensure persistence even after preventing seed production for several years (e.g., Schweizer and Zimdahl 1984). For Palmer amaranth, Menges (1987) reported that maintenance of a whole-season weed-free condition for six continuous years reduced the seedbank population by 98%, but the remaining 2% consisted of about 18 million seeds ha^{-1}. Thus, late-season weed escapes are substantial in a number of production systems, and the levels of seed production observed in these escapes can often be significant in meeting their functional roles within the production system.

Functional Roles of Weed Seeds

Weed seeds contribute to several functions within agricultural systems; some of the functions can be viewed as beneficial while others are detrimental. An understanding of the functional roles of weed seeds will help make informed management decisions regarding late-season weed seed production.

Agroecosystem Functioning. Weeds are typically viewed as impediments to crop production, but they play an important ecological role in promoting biodiversity in agroecosystems (Storkey and Westbury 2007). A diverse weed seedbank can promote diversity of various groups of macrofauna and microbiota (Franke et al. 2009); late-season weed seed production can greatly contribute to seedbank diversity. Further, weed seeds serve as a vital food source supporting higher trophic groups (Holland et al. 2006; Marshall et al. 2003; Taylor et al. 2006). In the U.K., results from farm-scale evaluations of genetically modified crops revealed the vital role of arable weeds in supporting farmland biodiversity (Hawes et al. 2003). Moreover, late-season weed escapes may promote *in situ* conservation of rare plant communities (Storkey and Cussans 2007). Evidence from crop-weed-insect interaction studies suggest that certain weeds play an important role in harboring a variety of beneficial insects that suppress crop pest populations (Altieri 1999). Carvalheiro et al. (2011) showed that farmland biodiversity can enhance crop productivity in certain situations. It has been argued that farmland biodiversity is vital to the sustainability and resilience of agroecosystems, and the benefits of arable weed communities in promoting biodiversity and agroecosystem functioning should not be overlooked (Butler et al. 2007). Detailed reviews on the role of arable weeds in agroecosystem functioning and resilience were completed by Marshall et al. (2003) and Franke et al. (2009).

Weed Species Persistence. Soil seedbanks promote the persistence of weeds by serving as weed seed reservoirs (Gallandt 2006). Weed seed rain, which is the reproduction and dispersal by weedy plants, is typically the chief contributor to seedbank replenishment (Simpson et al. 1989), and late-season escapes may greatly contribute to seed rain and seedbank

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increase (Cardina and Norquay 1997; Cavers 1983). Seed production in late-season escapes coupled with long survival in the seedbank is fundamental to the success of most arable weeds (Cavers and Benoit 1989). Studies have shown that late-season weed management is effective in reducing weed seed rain (Brewer and Oliver 2007; Clay and Griffin 2000; Taylor and Oliver 1997) and seedbank densities (Jones and Medd 2005). The contribution of early-season survivors to the weed seedbank is usually greater compared with late-emerging cohorts (Bosnic and Swanton 1997b; Steckel and Sprague 2004), because late-emerging weed seedlings are affected by crop competition, particularly for light. Seed viability, however, is known to be unaffected by reduced light supply (Baumann et al. 2001), and seed production in late-emerging weeds may sufficiently contribute to seedbank persistence (Mayen et al. 2008; Scursoni et al. 2007). Of particular significance of late-season weed seed production is the perpetuation and seedbank establishment of relatively new weeds to the production system. Thus, seed production in late-season escapes can play a vital role in seedbank persistence of arable weed communities.

Evolutionary Changes. Weed seed production has evolutionary implications within agricultural systems. Seed production contributes to the maintenance of genetic diversity within weed communities. New genetic combinations first appear in seeds, and this is the stage of life cycle where such diversities could be preserved long-term, through survival in the soil seedbank (Dekker 1999). Genetic diversity in turn facilitates weed adaptation to changing environmental conditions and management practices (Li et al. 2007). A species that exhibits different combinations of adaptive traits is more likely to survive long-term changes in habitat conditions (Dekker 1999). Of particular significance is the contribution to the evolution of herbicide resistance in weed communities. Natural mutations are capable of producing herbicide resistance alleles in weed communities (Jasieniuk et al. 1996), and the initial level of resistance alleles in a soil seedbank is directly and positively associated with the seedbank density. If more weed seeds are allowed to mature and replenish the soil seedbank, more is the probability for occurrence of resistance alleles in the soil seedbank, and vice versa. In this respect, modeling works have confirmed that production fields with high weed seedbank levels pose greater risks for the evolution of herbicide-resistant weeds compared with fields characterized by a good weed management history (Bagavathiannan et al. 2011b; Neve et al. 2011). In addition, increased weed seed rain from late-season escapes may reduce the efficacy of herbicide programs in subsequent crops (Taylor and Hartzler 2000), resulting in the exposure of weed populations to sublethal herbicide doses. It has been well-established that recurrent selection under sublethal herbicide doses can shift the weed populations towards higher tolerance levels (Manalil et al. 2011; Neve and Powles 2005; Norsworthy 2012). As such, seed production in late-season escapes may favor the evolution of herbicide resistance in arable weed communities.

Management Considerations

Weed Management Thresholds. The threshold concept lies in the core of weed management considerations, and management decisions for late-season escapes require an understanding of various thresholds available for weed management. The threshold concept was initially adopted to make more rational weed management decisions. The underlying principles of threshold-based weed management have been widely discussed (e.g., Cousens 1987), and ETs have been developed for a number of weeds in specific crops (e.g., Bosnic and Swanton 1997a). In particular, ETs have been widely applied to make management decisions in integrated weed management programs (Swanton and Murphy 1996). According to the ET approach, control action is taken if the estimated yield reductions are greater than costs of control, and based on this approach, control is rarely required for late-season weed escapes (Bauer and Mortensen 1992). Norris (1999) believed that application of the ET concept to weed populations, which was originally developed for insect pest control, is not ecologically sound. Norris proposed a no-seed threshold (NST) approach for weed management. Adopting the NST (i.e., zero threshold) approach for managing late-season weed escapes may be preferable in certain situations, notably for the management of new species or herbicide-resistant weeds. However, achieving and maintaining zero thresholds for late-season weed seed production will be difficult, if not impossible, in large production fields due to the associated costs and practical challenges. Such efforts could be justified only if they are feasible and the returns are greater than the investment, or the failure to do so will be disastrous (Panetta 2009; Wittenberg and Cock 2001). Simberloff (2003) argued that zero-thresholds (or eradication) should be considered for the management of a range of invasive organisms. While ET does not consider the long-term impacts of late-season weed seed production, NST-based weed management may not be feasible for the majority of arable weeds.

Unlike ET or NST, EOTs take in to account the long-term biological consequences of allowing late-season weed seed production, while considering the economic feasibility of management approaches (Cousens et al. 1986; Cousens 1987). Based on this, management is justified if the anticipated long-term benefits of controlling a given density of late-season weed escapes are greater than the current-season cost for control. The EOTs are established using EOT models, which include submodels for the biology of the species and the economic aspects of management (Bauer and Mortensen 1992). EOTs are usually lower than ETs and greater than NSTs. Bauer and Mortensen (1992) predicted that EOTs for velvetleaf (*Abutilon theophrasti* Medic.) and common sunflower (*Helianthus annuus* L.) control in soybean were 7.5- and 3.6-fold lower, respectively, than ETs calculated for these species. The EOTs for late-season weed control would be relatively lower for weed species with greater seed production potential and seedbank longevity. Bio-economic models developed by other researchers (e.g., King et al. 1986; Lybecker et al. 1991; Swinton and King 1994) followed a similar approach.

Although bio-economic models or its variants have been useful for making management decisions considering the long-term biological and economic impacts of weed seed production, their utility is limited in the context of establishing thresholds for herbicide-resistance management. To be specific, bio-economic models do not account for the genetic aspects of resistance evolution (mutation rate, mode of inheritance, dominance, and fitness), and in their original form they are not capable of monitoring the dynamics of

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resistance alleles in the seedbank in response to various management practices. In this regard, BERMs will be useful for establishing relevant thresholds (i.e., BERTs) for managing late-season weed escapes. These models will encompass within them submodels for the simulation of herbicide-resistance evolution and economics of available control options. The BERTs will be usually lower than EOTs, but higher than NSTs; weeds with high resistance probabilities and those that are difficult to control will typically require low BERTs for management. Monjardino et al. (2003) developed a bio-economic model for integrated resistance management of rigid ryegrass (*Lolium rigidum* Gaud.) and wild radish in Australia, and similar models could be developed to establish BERTs for systems that are vulnerable to herbicide resistance evolution.

Management Decisions Are Case-Specific. Because of the diverse functional roles (both advantageous and deleterious) of seed production by late-season weed escapes, application of a generic threshold is not realistic across a range of production systems, and the need or decision to prevent late-season weed seed production can be case-specific. The extent to which late-season escapes should be controlled depends on the type of weed, nature of problem, and goals and priorities of the production system (discussed below). The management decisions of producers are influenced by a set of ideologies and values that constitute the economic, social, and environmental elements (Swanton and Murphy 1996). However, such decisions should consider potential conflicts among the goals and possible long-term consequences.

Systems that practice conservation tillage with low-input and those that give importance to farmland biodiversity may not readily adopt late-season weed management, unless such infestations reach economically damaging levels in the short term. In production systems where economic returns is the priority, which is usually the case in a number of systems, allowing late-season weed seed production solely based on current-season cost saving may not be appropriate (Coble and Mortensen 1992). It will be often more economical over the long run to manage late-season escapes, particularly for the problematic weeds (Cardina and Norquay 1997; Mayen et al. 2008; Sattin et al. 1992).

Van Acker (2009) suggested a trait-based weed class system to determine case-specific need for managing late-season weed escapes, recommending that growers make management decisions based on the seed production potential and seedbank longevity of specific weeds. According to this criterion, late-season weed management is justified for weeds that are prolific and persistent. Sattin et al. (1992) suggested that the ET-based management decisions should not be adopted for problematic weeds such as velvetleaf, which can survive in the seedbank for up to 50 yr (Warwick and Black 1988). Failure to treat a subthreshold population of late-season escapes in one year may influence whether or not the threshold is exceeded in the following years (Cousens et al. 1986). For instance, Cardina and Norquay (1997) reported that allowing a single-season seed rain (based on ET) in velvetleaf will require 90% control annually to maintain the weed population at levels below ET over a 5-yr period, whereas $>$ 95% control would be required if seed rain is allowed each year. Additional considerations to managing late-season escapes include history of occurrence of a species in the field (i.e., relatively new vs. commonly occurring), seed dissemination ability, difficulty of control, and likelihoods for the escapes being herbicide-resistant (Van Acker and Bartlinski 2005). If late-season escapes comprise weeds that are relatively new to the production system, especially if they are known to be problematic, then control measures are warranted.

Preventing late-season weed seed production is critical in production systems that are vulnerable to herbicide resistance evolution, notably systems with intensive cultivation of herbicide-resistant crops with inadequate crop/herbicide rotation (Norsworthy et al. 2012). Late-season weed management is important in these circumstances because it is likely that the escapes may comprise resistant individuals (Davis et al. 2008). Preventing late-season seed production is particularly important for weeds that possess characteristics that favor resistance evolution. Weeds that are prolific with rapid seedbank turnover (i.e., low dormancy and greater recruitment) are of greater concern. Prolific seed production increases the probability for the occurrence of the resistance mutant (Jasieniuk et al. 1996), which coupled with high seedbank turnover leads to more plants being exposed to the herbicide, increasing the rapidity of selection for the resistant mutant.

In addition to preventing seedbank persistence and future weed problems, late-season weed control will benefit many growers through increases in harvest efficiency and prevention of weed seed contamination of crop produce (Griffin et al. 2010; Norsworthy 2004). A weed management survey conducted among Illinois growers revealed that growers are typically concerned about harvest problems associated with weed escapes (Czapar et al. 1997). Weed seed contamination may increase moisture content and deteriorate the purity of crop seed/quality of produce, reducing grade and market value (Griffin et al. 2010; Willard and Griffin 1993). For example, weed seeds and debris can contaminate cotton lint during harvest, and these contaminants need to be removed during the ginning process to ensure market value. In the Mississippi Delta region, most cotton growers set a low tolerance level for weed escapes due to the contamination issue (K. L. Smith, personal communication). Ellis et al. (1998) reported improvements in soybean seed quality with late-season weed control measures.

Grower decisions as to whether or not to manage late-season weeds may also be influenced by the availability of government support through environmental stewardship programs for such practices, although the requirements and nature of support may vary across regions depending on program goals and priorities. In Europe, the reforms of Common Agricultural Policy subsidies, particularly "decoupling," which separated subsidy payments from crop production (POST 2005) and programs such as the Single Payment Schemes in the U.K. that are based on "cross-compliance" standards (POST 2005; Rural Payments Agency [RPA] 2011), provided late-season escapes of arable weeds with some economic value to the farmers (Storkey and Westbury 2007). In the United States, growers are eligible to receive \$136 ha^{-1} if they follow a number of integrated pest management techniques to address herbicide resistance in weeds, which include regular field scouting through postharvest and application of postharvest burndown herbicides to prevent weed seed production (Natural Resources Conservation Service [NRCS] 2011). Therefore, growers need to assess the situation and make management decisions taking into account the potential long-term consequences of allowing late-season escapes and goals and priorities of the system; bioeconomic models (or BERMs) will facilitate management decisions by growers. The following strategies will be useful for managing late-season weeds.

Management Strategies. Management recommendations made in this review mainly focus on preventing seed production and seedbank replenishment by late-season weed escapes. For seedbank management, readers can consult other sources, notably Buhler et al. (1997), Davis (2006), Gallandt (2006), and Kremer (1993).

Planting to Preharvest. The key to successful weed control and prevention of escapes relies on an understanding of the phenological development of weed species and appropriate timing of control measures (Huang et al. 2001; Otto et al. 2007). Control measures aimed at relatively smaller seedlings are typically effective, while management attempts carried out on bigger weeds often lead to poor control and substantial in-crop weed escapes (Hartzler 2001). Weeds also escape control interventions simply by emerging after such measures have ceased; therefore, an understanding of the weed emergence patterns may facilitate weed control timing (Grundy 2003; Jha and Norsworthy 2009; Page et al. 2006).

For late-season weeds, seed production is the primary concern rather than biomass accumulation because of their limited interference with crops (Baumann et al. 2001). Late-season preharvest herbicide applications can be used to minimize seed set in weed escapes. Bennett and Shaw (2000) showed that application of preharvest desiccants in soybean was effective in reducing seed production and viability of a number of weed species. Appropriate choice of herbicide, rate, and timing of application may be critical to achieve better results. In field pennycress (*Thlaspi arvense* L.), application of MCPA or tribenuron-methyl at beginning of bolting (1 to 15 visible buds) totally prevented seed set, whereas application 9 d past this stage resulted in substantial seed production (Andersson 1995). Fawcett and Slife (1978) found that application of 2,4-D prior to or just after flowering of common lambsquarters and jimsonweed (*Datura stramonium* L.) reduced seed production by 99 and 100%, respectively.

Late-season POST application of a nonselective (broad spectrum) herbicide to reduce weed seed production in crops is known as crop topping (Steadman et al. 2006; Walsh 2001). Nonselective herbicides with systemic activity such as glyphosate can be particularly valuable for use in crop topping (Steadman et al. 2006). In wild oat (*Avena fatua* L.), Shuma et al. (1995) reported that application of glyphosate at anthesis totally prevented viable seed production. Clay and Griffin (2000) found that crop topping with glyphosate at the early seed-set stage reduced subsequent emergence for common cocklebur (*Xanthium strumarium* L.) and hemp sesbania (*Sesbania exaltata* Rydb. Ex A.W. Hill) by 82 and 94%, respectively. Steadman et al. (2006) showed that crop topping with glyphosate was most effective at reducing seed set of rigid ryegrass when applied during heading and anthesis, whereas paraquat plus diquat was effective when applied during the milk and early dough stages. In the same study, the authors found that these nonselective herbicides also reduced seed viability and seedling fitness. The effectiveness of glyphosate or paraquat in reducing viable seed production (~90% reduction) of annual ryegrass was also reported by Mayfield and Presser (1998). The efficacy of crop-topping would, however, be lower for weed species that exhibit indeterminate growth characteristics (Walsh 2001). Management efforts to prevent seed production or viability in late-season escapes need to be relatively inexpensive (Biniak and Aldrich 1986). Rope-wicks (Dale 1978; Keeley et al. 1984; Moomaw and Martin 1990) or recirculating sprayers (Carlson and Burnside 1981) can be used to economically treat weed escapes that grow taller than the crop canopy.

Although most growers rely heavily on herbicide-based weed management, they can certainly benefit from the integration of other strategies that involve relatively minimal input and management costs. Lindquist et al. (1995) demonstrated that combining EOTs with nonchemical strategies increase economic returns and reduce herbicide use. Nonchemical strategies will greatly supplement herbicide-based weed control programs rather than making them redundant (Bastiaans et al. 2007). Most importantly, nonchemical approaches help reduce the frequency of application of herbicides and help preserve the long-term utility of available herbicides by minimizing selection pressure and delaying resistance evolution (Norsworthy et al. 2011). Cultural approaches such as using competitive cultivars, adjusting planting date, altering planting density, intercropping, and cover cropping can be very effective (Bond and Grundy 2001; Malik et al. 1993; Norsworthy et al. 2011). Planting soybean as a drill-seeded crop with narrow-row spacing was shown to drastically reduce seed production in barnyardgrass cohorts emerging as early as 3 wk after crop emergence, whereas considerable seed production was observed for up to 6 wk after crop emergence when soybean was planted as a wide-row crop (Bagavathiannan et al. 2011d). The key with these approaches is to exploit crop competition to suppress late-emerging weeds, which would not only reduce seed production, but also undermine the competitive ability and reproductive potential of the offspring (Baumann et al. 2001). Cultural strategies could be integrated with herbicide options to achieve efficient prevention of seed production in weed escapes.

There exist a number of other nonchemical approaches to managing late-season escapes. In row-crop production systems, except when cultivation is prohibited (due to conservation tillage, tuber crops, or possible damage to roots), late-season cultivation may be effective in controlling weed escapes (Vincent et al. 2001). Mechanical cultivation when combined with proper timing of herbicide application can be particularly effective in controlling perennial weeds (Bruff et al. 1996). Walsh and Powles (2007) suggested the use of hay cutting and swathing at crop maturity to prevent ryegrass seed production. In certain situations, growers implement physical weed management to prevent seedbank renewal of problematic weeds. For example, late-season hand chopping of Palmer amaranth has been practiced by many cotton growers in the Midsouth U.S. to prevent the perpetuation of any possible resistant plants, although it is an expensive practice in the short-term (J.K. Norsworthy, nonpublished observations).

At-Harvest. The harvesting operation typically facilitates the removal and dispersal of seeds from uncontrolled weeds (Shirtliffe and Entz 2005). However, it presents an opportunity to collect and destroy any nonshed weed seeds prior to their return to the soil seedbank (Walsh 1996). Weed seed collection at harvest could be achieved in a number of ways, but most of them involve some type of attachment to the existing harvest machinery. Walsh and Parker (2002), using a chaff-cart attached to the rear of the harvester, achieved up to 85% efficiency in removing annual ryegrass seeds in Australia. The chaff containing weed seeds could then be destroyed or composted to kill weed seeds. Walsh and Powles (2004) suggested the use of baling equipment attached to the harvester to bale the chaff along with weed seeds that could be later fed to confined livestock. Another strategy is to windrow chaff as it exits the harvester and subsequently burn it; high temperature conditions during burning can kill weed seeds. Studies by Fettell (1998) and Walsh and Newman (2007) reported about 98% control of annual ryegrass following crop residue burning. Making weed seeds nonviable as they are expelled from the harvester will be more effective than chaff collection. In Australia, a farmer-developed Harrington seed destructor (HSD) has been successfully used to grind weed seeds and destroy them before they reach the soil. In field evaluations, the HSD consistently destroyed between 95 and 98% of ryegrass seed present in wheat (*Triticum aestivum* L.), lupin (*Lupinus* spp.), and barley (*Hordeum vulgare* L.) chaff (Walsh 2010).

Postharvest. Weed seedling emergence and seed production after crop harvest can be substantial in certain situations. For example, in the Pacific North West, Russian thistle (*Salsola tragus* L.) emerging after small grain harvest can attain reproductive maturity and produce about 17,000 seeds plant^{-1} prior to the killing frost (Young 1986). In these situations, management attempts to prevent late-season weed seed production should extend beyond in-crop weed control. Such practices would also help control winter annual weeds and tough-to-control perennials (Flaten 2009). Postharvest weed control could be achieved in a number of ways, including but not limited to herbicides, fall tillage, mowing, and cultural strategies such as double cropping or cover cropping. Young and Whitesides (1987) achieved up to 96% control coupled with 64% reduction in seed germination of Russian thistle using a postharvest herbicide application. Well-timed in-crop soil residual herbicides can reduce the emergence of postharvest weeds; thus, in-season weed control programs should consider the value of residual herbicides in postharvest weed control. Fall tillage operations can control summer annual weeds as well as perennials that are tough to control using herbicides. Fall tillage, when carried out using implements such as moldboard plow, can bury newly shed weed seeds to depths below the zone of emergence, preventing successful recruitment (Devore et al. 2009). When timed prior to seed set, mowing can be effective in preventing seed production in postharvest summer annual weeds, although this practice is more effective on broadleaf species than on grasses due to differential growth habit (Meiss et al. 2008). Cultural practices such as double-cropping (e.g., early-planted soybean followed by winter wheat, Devore et al. 2011) or cover cropping (e.g., fall rye [*Secale cereale* L.], Blackshaw 2008) can greatly decrease the opportunities for summer annuals to emerge and reproduce after harvesting the main season crop. In these situations, tillage operations carried out to establish the fall crop can eliminate the postharvest recruits prior to planting, whereas crop competition can reduce subsequent emergence. In warmer regions where fallows are practiced, efforts should be made to prevent weed seed production using the above approaches where suitable.

Limitations to Managing Late-Season Escapes. While managing late-season escapes can be valuable, promoting late-season weed management in view of the anticipated long-term benefits can be difficult to achieve in a number of circumstances. Some herbicides are injurious to crops when applied during late-season, causing yield penalties (Biniak and Aldrich 1986; Hager et al. 1999). For instance in soybean, POST application of paraquat prior to physiological seed maturity (3 to 4 wk before harvest) reduced soybean seed weight and yield (Whigham and Stoller 1979). Many POST herbicide applications have to satisfy a minimum interval requirement between application and crop harvest due to the risk of herbicide residues in the produce as well as injury to the crop (Hager 2011). Furthermore, there are late-season herbicide use restrictions considering the residual activity on the subsequent crop in rotation (Hager et al. 1999). Herbicides remain the most efficient and convenient tool for weed control for many growers, and any use restrictions limit grower adoption of late-season weed control practices.

At-harvest practices such as chaff collection, baling, and seed destruction constitute additional equipment and management costs, while windrow burning can be environmentally harmful and may not comply with local restrictions (Walsh and Powles 2004). Fall tillage is not advisable in systems adopting conservation-tillage practices due to soil erosion and moisture loss. Because the perceived benefits of late-season weed management are long-term, it is likely that some growers particularly those who lease or rent the land find it less attractive. Additionally, there exist knowledge gaps, which make it uncertain among the growers and weed managers of the effective ways to managing weed escapes, ultimately limiting the adoption of late-season weed control.

Future Research Needs

Additional field research is important to thoroughly understand the phenological development of weeds in relation to time of emergence in crops. Research is necessary to establish the heat unit requirement for the various developmental stages of prominent weed species in order for timing management interventions. If heat units needed for viable seed production are known, the extent of time that late-season weed escapes need to be managed can be estimated using historical weather data. Knowledge of heat units needed for flowering to seed set will greatly facilitate crop-topping applications, because the effectiveness of this strategy depends on the timing of implementation.

The contribution of late-season weed seed production to seedbank replenishment, population dynamics, and the evolution and spread of herbicide resistance needs to be thoroughly investigated; robust population dynamic models will be useful for this purpose. Equally, development of BERMs will be necessary to establish BERTs for production systems vulnerable to herbicide-resistance evolution. More emphasis on characterizing the ecology and biology of specific weed species is important for model parameterization.

There are knowledge gaps on effective management tactics for late-season weed escapes. Knowledge of the effect of the choice, rate, and timing of preharvest herbicide applications

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on weed seed production and viability is lacking for a number of important arable weed species. Research is also necessary to develop better tools and equipment for managing late-season weed escapes. Advanced tools and technologies such as remote sensing and geographical information systems need to be employed to facilitate the mapping and spot treatment of weed escapes in large production fields. In addition to cost savings, these approaches may reduce herbicide use and associated environmental impacts. The integration of nonchemical approaches is vital for the long-term sustainability of weed management programs, but knowledge is limited in this respect to enable implementation. More research emphasis on nonchemical strategies for minimizing late-season weed seed production is critical, given the value of these tactics in delaying the evolution of herbicide-resistant weeds. BERMs will be helpful to identify suitable ways to integrate nonchemical approaches for mitigating herbicide resistance evolution.

Late-season weed management goals to minimize the long-term impact of weed seed production on profitability and goals to promote agroecosystem functioning need not be mutually exclusive and these goals may coexist. Ideally, crop production systems should strive to prevent the long-term economic consequences of weed infestation, while trying to exploit the functional benefits provided by weed communities. Storkey and Westbury (2007) proposed that weeds could be ranked in terms of their biodiversity value and competitiveness with crops; thus, management attempts can focus on problematic weeds with less biodiversity value, allowing beneficial weed groups with low competitive ability to thrive. Another proposed approach is to sow field margins with diverse weed communities for promoting farmland biodiversity, while keeping the crop fields weed-free throughout the season as much as feasible (Meek et al. 2002). Alternatively, set-aside lands have been suggested as a way to conserve rare arable weeds and promote biodiversity in intensively farmed areas (Boatman et al. 2011; Neve et al. 1996). However, these approaches have numerous practical challenges and limitations (Cordeau et al. 2011). For example, Blumenthal and Jordan (2001) showed that field margins contribute to the persistence of problematic weeds such as Canada thistle [*Cirsium arvense* (L.) Scop.] in arable fields. Furthermore, there are knowledge gaps that limit the adoption of these strategies. Given the mounting issues of herbicide-resistant weeds and the concurrent need to preserve the biodiversity and sustainability of agroecosystems, research is required to develop tools and knowledge to effectively utilize the ecological benefits of weeds, while minimizing their impact on crop production. Such developments would facilitate appropriate management decisions for late-season weed escapes.

In summary, preventing weed seed production is vital for preventing future weed problems, but the extent to which management is necessary depends on individual circumstances. One should use discretion, taking into account the long-term biological and economic impacts of allowing late-season weeds to produce seeds. When economic weed management is a priority, adoption of an EOT or BERT approach will be useful in making appropriate management decisions. Until such models are developed and available for utilization in specific situations, managing late-season weeds is valuable for production systems with high risk of evolving herbicide-resistant weeds and for systems with substantial late-season weed seed production. At any case, a diversified approach to weed management, one that utilizes nonchemical tactics where possible, is fundamental to sustainable weed management. Research is necessary to address the knowledge gaps identified in this manuscript to facilitate informed decision making by growers.

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