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Review

Shifting the Paradigm: An Ecological Systems Approach to Weed Management

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Abstract: Weeds have been historically, and are still today, the primary and most economically important pest in agriculture. Several selection pressures associated with weed management, such as an overreliance on herbicides, have promoted the rapid evolution of herbicide-resistant weeds. Integrated Weed Management (IWM) is promoted as an ecological systems approach, through the combination of biological, chemical, cultural, ecological, and mechanical control methods. The concept of a systems approach is defined as managing weeds by combining practice and knowledge with the goals of increasing yield and minimizing economic loss, minimizing risks to human health and the environment, and reducing energy requirements and off-target impacts. The reliance on herbicides in modern cropping systems has shifted the management focus from requiring intimate knowledge of biology, ecology, and ecological systems to herbicide chemistry, mixes, and rotations, application technology, and herbicide-tolerant crop traits. Here, an ecological systems approach is considered, examining new trends and technologies in relation to IWM and weed ecology. Prevention of spread, seedbank management, crop rotations, tillage, cover crops, competitive cultivars, biological weed control, and future solutions in concept-only are presented, and knowledge gaps are identified where research advancements may be possible. An ecological systems approach will provide improved stewardship of new herbicide technologies and reduce herbicide resistance evolution through diversification of selection pressures. Agroecological interactions should be studied in light of new, developing weed control technologies. The science of weed management needs to refocus on the foundations of weed biology and ecology to enable an ecological systems approach and promote agricultural sustainability.

Keywords: biotechnology; cover crops; harvest weed seed control; herbicide resistance; IWM; Integrated Weed Management; precision agriculture; soil seedbank; weed ecology

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1. Introduction

Weeds are the primary and most economically important pest in agriculture today [1]. Weeds have always been an issue in agriculture and have successfully avoided control attempts [2,3]. Weeds have certain characteristics that distinguish them from other plants; specifically, they are successful colonizers, survive in a wide range of environmental conditions, are prolific seed producers, and grow rapidly. These characteristics aid them in effectively competing with crops for resources such as light, nutrients, and water [4], and may allow rapid evolution of weeds in response to management scenarios [5–7]. The current management paradigm in large-scale industrial agricultural systems relies heavily on the use of herbicides for weed control. The natural traits of weedy plants, coupled with the increase in evolution of herbicide resistance (HR), account for challenges in current weed control programs [8].

Integrated weed management (IWM) is defined as the practice of using chemical, mechanical, and biological control methods in combination, such as diverse herbicide sites of action, cover crops, harvest weed seed control, crop rotations, competitive cultivars, narrow row spacing, high seeding rates, directed fertilization and irrigation, tillage, and biocontrols, to control weeds, with a strong emphasis on the principles of weed ecology [9,10]. However, ecological systems are exceptionally complex. The mechanisms underlying natural systems may be studied and understood in isolation, but the derived inferences may not hold true across a range of scenarios [11]. Ecological management of agricultural weeds requires intimate knowledge of the local environment, and the use of herbicides has changed the type of skills and knowledge used to manage weeds [9]. Over time, there has been a shift from knowledge of management regarding biology and ecology and ecological systems of the weeds and crops towards knowledge of management using herbicides, herbicide rotations and diverse sites of action, and stacked crop traits. Some ecological practices may be difficult or impossible to implement in certain geographies or with the available tools on the farm. The basis of effective weed management is cropping system temporal and spatial diversity [12], which serves to increase ecological complexity. However, an increase in ecological complexity may be associated with a decrease in predictability. In a series of listening sessions on HR weed management hosted by the United States Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS, Riverdale, MD, USA), the United Soybean Board (USB, Chesterfield, MO, USA), and the Weed Science Society of America (WSSA, Westminster, CO, USA), growers asserted that diverse management programs are difficult to establish and the current economic realities are not conducive to change [13]. This point is important; economic hardships will impact growers' ability to adopt alternative, ecological methods.

The objective of this paper is to outline some ecological approaches to weed management, which may serve as components of an IWM system. Many of these are traditional concepts, which need to be analyzed under the lens of new technology. Knowledge gaps are identified, where possible, citing potential areas for future research. Not all ideas and initiatives are from the peer-reviewed literature, and therefore, should serve as a starting point for future discussion. Advances in robotics and artificial intelligence are also discussed as potential tools in an IWM approach, and in the hope that these new technologies do not detract from the need for ecological solutions. There are many social, cultural, and economic challenges to successful implementation, but a shift in thinking must begin now to allow time for grower communities to adapt and ecological knowledge to grow.

2. New Angles on Ecological Solutions

2.1. Prevention of Contamination and Propagule Spread

While best management practices may slow the evolution of weeds, weed propagules move across the landscape in a variety of ways. The practice of sanitation (equipment cleaning) is viewed as a highly effective best management practice, but is not frequently adopted by growers (Table 1) [14,15]. Movement of machinery (e.g., contract harvesters) increases risk of propagule spread. Equipment washing is difficult, time consuming, often impractical, consumes water, etc. There are logistical challenges to setting up centralized equipment wash stations, but the technology to do this effectively does exist; equipment operators could carry mobile wash equipment and factor time into contracts to clean equipment from field to field [16]. Grain contamination at harvest is not only a problem for grain sales but can also distribute weed seeds across wide geographies along transportation corridors. One potential solution, in addition to already-implemented post-harvest cleaning practices, would be to modify hauling technologies to adapt truck beds with perforations and catchment underneath; seeds would settle out during transport and can be destroyed at the elevator (D. Sammons, personal communication). Growers also understand the importance of planting weed-free seed [14,15], and following the high-profile cases of Palmer amaranth (*Amaranthus palmeri* S. Watson) contamination in cover crop and conservation seed mixes, an assay was developed to test for Palmer amaranth in bulk mixed seed samples [17]. However, even with a focus on prevention, research has shown that waterfowl may move *Amaranthus* spp. seed up to 2900 km [18]; therefore, seed may move great distances with animal vectors, and growers should proactively manage their fields with a spatially and temporally diverse IWM program.

Table 1. Areas for action and additional research, and identified knowledge gaps.

Prevention
• Improve and promote sanitation practices to prevent the movement of weed seed between fields. • Work with engineers to design, modify and market equipment to manage weed seeds. • Develop grower networks for sharing specialty equipment, knowledge, and support, among growers and with extension specialists, researchers, and industry personnel; coordinate weed management issues across property lines and geopolitical boundaries. • Create economic or social incentives for preventative strategies and ecological approaches.
Soil Seedbank Management
• Discuss the importance of long-term management of the soil seedbank with growers. • Explore how the interactions of various ecology based IWM practices drives the reduction of the soil seedbank. • Test how harvest weed seed control (HWSC) and cover crops, alone or as an interaction, fit into a standard production system. • Collect data across regions to determine rates of seedbank decline using various methods to manage the seedbank.
Tillage, Cover Crops, and Intercrops
• Identify and promote more crop options in rotation with corn and soybean. For example, industrial hemp and cover cress may be future options. • In cases where tillage must be used, develop recommendations to compensate for negative effects, such as the integrated use of cover crops, crop diversification, and addition of amendments and residues, or the use of rotational tillage with cover crops and amendments. • Begin to seek new high residue cover crops that will parallel the success of cereal rye in weed suppression. • Herbicide systems should be optimized for efficacy in high residue cover crop scenarios. • Work with growers to provide ways to overcome cover crop challenges and minimize associated risks to ensure profitability. • Identify and breed for competitive crop traits; the use of competitive cultivars is commonly recommended, yet growers have little assistance in identifying cultivars with this trait. • Provide recommendations on seeding rates, row spacing, and row orientation to optimize weed suppression and crop yield. • Determine if interseeding and relay cropping can be feasible and profitable in soybean systems.

Table 1. *Cont.*

Biological Weed Control

- Study the interactions between weeds and microbes; there are cases of successful weed control products that have been developed from fungi, bacteria, and viruses.
- Quantify how microbial stimulants or additives may increase crop competitive ability against weed species, and ensure that microbial stimulants and additives are not also increasing weed competitive ability or evolutionary success.
- Encourage weed seed predators in agricultural fields by promoting the creation of complex habitat ("beetle banks", field margins).
- Study ecological associations between cover crops, crop pests, and beneficial insects to improve the functioning of the system. These relationships will vary across geographies.
- Determine the interactions between seed predators and cover crop monocultures or mixtures.
- Seek targeted pest control solutions that do not impact beneficial insects.

New (Currently Proposed) Solutions to Integrate within an Agroecological Approach

- Future weed control options may integrate RNA interference (RNAi) and Clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR-associated protein 9 (CRISPR/Cas9) technologies.
- Technological advances will allow the integration of ecological approaches with weed control technologies, such as Spot and Spray/See and Spray technology, variable rate applications, autonomous tractors, targeted tillage, unmanned aerial vehicles, weeding robots, laser weeding, stamping, microwaves and radiation, electrical discharge, flaming, pressurized air, solar irradiation.

Overall Needs

- Conduct research at multiple scales; ecological interactions are not well documented and understood and may rely heavily upon geographically specific factors.
- Complex studies require a minimum of 3 to 5 years of research funding, which is often difficult to obtain and ensure.
- Grower education, as well as the education of future weed scientists, in the fields of weed biology and ecology is a critical investment.

Grower networks could be a valuable support tool, and would allow for the sharing of specialty equipment, such as interseeders, cover crop roller crimpers, industrial hemp decorticators for fiber, etc. One of the most successful approaches in herbicide resistance management has been a community-based approach, where growers design programs to manage herbicide-resistant weeds in cooperation with academic, government, and industry representatives [13,19]. Growers may feel that herbicide resistance issues will worsen because of the action of their neighbors or others throughout the region, a common pool social dilemma [13,20], however, encouragement should be provided by studies [21,22], which show that following a robust management program, even when other nearby farmers are not, will still result in a higher return on investment compared to not using best management practices [13]. A grower network, such as the one initiated in two counties in Arkansas, United States, for control of HR Palmer amaranth, may be helpful in tackling the landscape-scale issue of herbicide resistance and weed evolution [7,23]; solutions will need to be coordinated across property lines and geopolitical boundaries [20]. Additionally, economic incentives that support change are needed. It is difficult for growers to increase ecological complexity within their cropping systems, when complexity often brings unpredictability due to the emergent qualities of ecological interactions [24].

2.2. Seedbank Management

Historically, management strategies of the soil seedbank have focused on the short-term reduction of the most troublesome weeds in a field based on annual economic thresholds, without a specific focus on the long-term ramifications of soil seedbank management [25,26]. The importance of the weed seed bank, specifically, has been evaluated most heavily through weed seed survival and emergence studies. These studies typically saw that the persistent use of cultivation and herbicides will often reduce the weed seed bank, but with the increase in HR weeds or less than perfect weed control, eliminating them altogether is rarely achieved.

A biological characteristic of many important weeds is that the majority of seeds are retained on the plant at maturity [27]. For example, U.S. soybean Palmer amaranth and common waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) retain greater than 95% of their seed at harvest [28]. In Australian field crops, similar levels of seed retention are seen in annual ryegrass (*Lolium* spp.) (~80%), wild radish (*Raphanus raphanistrum* L.) (99%), bromegrass (*Bromus* spp.) (77%), and wild oats (*Avena* spp.) (84%) [29]. Similar results have been documented for many weed species in several of the world's major grain producing regions, such as Spain, the United Kingdom, Canada, Argentina, Italy, and Sweden [30]. The concurrent maturation of crop and weed may be beneficial for the weed, because the retained weed seeds can be collected by the combine at harvest. This subsequently disperses the weed seeds behind the harvester and potentially increases the mixing of genetic material [31]. Additionally, the collection of weed seed at crop harvest can lead to grain contamination, which can aid in weed dispersal within a field [25]. This concurrent, biological attribute allows weed seeds to be targeted at harvest.

Harvest weed seed control (HWSC) is a non-chemical weed management tactic that targets weed seeds at harvest, which results in reducing the number of seeds entering the soil seed bank [32]. There are six forms of HWSC implemented today: chaff carts, bale-direct systems, narrow windrow burning, chaff lining, chaff tramlining, and seed destructors (i.e., integrated Harrington Seed Destructor (iHSD)) [26,30,33,34]. All of these systems target the chaff fraction of harvest residues, which typically contains the majority of the weed seed [35], and have been shown to be highly effective [30]. HWSC is being heavily adopted by Australian growers (43% as of 2014) and is estimated to grow by an additional 39% by 2019. In U.S. cropping systems, however, HWSC adoption is limited. This is likely due to limited research in U.S. crops and the lack of grower knowledge of this IWM tactic.

Although HWSC has shown great success, it does not come without its limitations. For example, increasing moisture content of the chaff can lead to the iHSD mill to clog [26], reducing efficacy slightly [30], or to not allow a crop to burn as efficiently. It is also important to note that over-reliance on HWSC for weed control, as with any IWM tactic, will eventually lead to the loss of this tool. It is expected that weed populations will quickly adapt to HWSC systems if practiced heavily without any additional, diverse management tactics. Potential weed adaptations could be early seed maturity, reduced seed retention, plants that reproduce below harvest height, and erect to prostrate vegetative growth. Thus, HWSC tactics must be used responsibly and as a supplementary weed management tactic. A grower focus on the seedbank will help drive the reduction in aboveground weeds and require acquisition of biological and ecological knowledge.

2.3. Crop Rotation

The current rotational system is simplified, which favors weed survival and promotes the evolution of superior competitive ability of weeds over time [5,6]. Field crop production in central United States corn (*Zea mays* L.) production geographies, such as Iowa, commonly consist of a 2-year rotation of corn and soybean crops [12]. Simplified rotational practices may be heavily dependent upon herbicides to control weeds and maintain crop yields [36]. In a comparison of 2-, 3-, and 4-year rotations in an 8-year study in Iowa, herbicide use was reduced by 88% in the 3- and 4-year rotations, compared to the 2-year rotation, while weed management was equivalent across all rotations [12]. Potential drawbacks of crop rotations would be the economic risk associated with alternative crops, using crops in successive rotation that require similar management, lack of consistent weed response, and lack of supporting research to evaluate diversified rotations in regards to weed management [37,38]. There is a need for more research regarding complex rotational programs, and there is a need for more rotational crop options that could also provide additional, diversified sources of income.

Two examples of potential new crops on the horizon in the United States are industrial hemp (*Cannabis sativa* L.) and cover cress (Brassicaceae, *Thlaspi arvense* L.), genetically modified from the winter annual weed species field pennycress (*Thlaspi arvense* L.). Much scientific research and market infrastructure is needed before these crops can provide rotational diversification. Legalized by the 2018 Farm Bill, products from industrial hemp are numerous, and hemp may be grown for fiber, seed or and seed oil, and cannabidiol. The methods of production for each commodity are different and will result in different agroecological impacts and economic scenarios [39]. At present, there are no herbicides or pesticides labeled for use in industrial hemp in the United States. Therefore, it is important that the fiber or seed crop establishes early and initially outcompetes weeds. Given the right conditions, industrial hemp is purportedly a highly competitive crop and may suppress weeds in the field, but more research is needed to confirm this assertion [40]. The ecological impacts and the potential effects of industrial hemp on weeds and weed seed banks will establish a new field of research. Additionally, cover cress is a potential new oilseed crop, which may be grown across temperate regions. Plants in the Brassicaceae family are known to produce glucosinolate, a compound implicated in suppression of weeds [41]. While the glucosinolate amounts produced by cover cress are unknown and may depend upon variety and genetically modified traits, cover cress may offer a new, potential weed-suppressing winter crop to corn-soybean rotations. As farms have continued to grow larger, ecological management practices, such as long rotations, intercropping, and other traditional practices, such as the integration of livestock into cropping systems, become less common [9]. Research is needed to aid large-scale growers, so that these practices may become feasible and profitable.

2.4. Tillage

Traditional organic agriculture has been highly reliant upon tillage to provide weed control. Typical practices in organic grain production involve moldboard plow or disc tillage, the use of a tine weeder or rotary hoe, and interrow cultivation [42]. Although tillage may be very effective in controlling weeds and depleting the weed seedbank, tillage may negatively impact soil conservation, promote soil erosion [37], reduce root colonization by arbuscular mycorrhizal fungi [43], and lead to soil carbon loss from the soil [44]. Some research has shown that the use of cover crops, crop diversification, soil amendments, and the return of residues to the soil may potentially compensate for negative effects of periodic tillage [42,45,46], and rotational tillage systems with cover crops or manure may reach higher levels of organic matter than no-till systems [47]. However, tillage is not part of a conservation agriculture approach [38], and shifts to no-till agriculture will cause a shift in weed community from annual broadleaf species to annual grasses and perennials [38]. Advancements in precision agriculture may encourage the use of spot-tillage, strip-tillage, and inter-row cultivation for weed control, while still maintaining some soil conservation benefits of no-till [48–50], but more research is needed to fully integrate these practices into an IWM approach. In modern organic systems, there seems to be a movement away from tillage and towards the use of high biomass cover crop residue to control weeds in systems.

2.5. Cover Crops

Weed suppression in organic no-till systems using cover crop biomass only became possible with the introduction of the roller-crimper [51]. The use of cereal rye (*Secale cereale* L.) forms the basis for this strategy in soybean, with mechanical termination and the use of a roller-crimper. Greater than 8000 kg ha $^{-1}$ of cereal rye biomass has been determined to be the threshold for annual weed suppression, with challenges posed by early-emerging annual weeds, high seedbank densities of weeds (over 10,000 seeds m $^{-2}$), and perennial species [51]. It would be predicted that the weed community would shift towards large-seeded species able to grow through this residue layer. More high-residue cover crop options besides cereal rye are needed to diversify this practice. In a survey of non-organic grower perceptions on herbicide resistance management, growers have suggested that cover crops can present challenges, and there are few available profitable crops to rotate with corn and soybean [13]. Diversity in crop rotations is recognized as an effective herbicide resistance management tactic because different herbicide sites of action can be used on different crops, which can diversify this management tactic [25]. Knowledge gaps include unknown or unanticipated cover crop residue and herbicide interactions, overcoming interference of weather and crop planting or harvest with optimal timing of cover crop planting and termination, and ecological interactions with weather and biota, such as influence on weed, pest, and pathogen populations. Research in this field should continue to support growers in overcoming these challenges, minimizing risks, and improving profitability of these systems.

2.6. Competitive Ability of Crops

Besides planting a diverse cover crop mixture, there are other ways to increase spatial diversity within cropping systems to suppress weeds. Crop competition is an approach that can be used to manage weeds to reach the ultimate goal of improved crop production. Enhanced crop competition can be achieved through various cultural practices, such as competitive crop cultivars, increased seeding rates, narrow row spacing, and altered row orientation [52–55]. Crop competitiveness has the potential to reduce crop yield losses from weed interference and avoid weed seed bank replenishment by reducing weed growth and preventing future infestation. While several studies have looked into competitive cultivars [56–59], none of them have shown that weed-competitive crops based on morphological characteristics are reliable enough to be pursued much further by breeders because plant traits are rarely independent and the diversity among and within cultivars is vast.

Growers are using interseeding, relay cropping, bio-strips or track-strips, and innovative crop rotations. Penn State University and Cornell University have been leading in research on interseeding cover crops into cash crops, showing no effects on yield when cover crops such as crimson clover (*Trifolium incarnatum* L.), radish (*Raphanus sativus* L.), and hairy vetch (*Vicia villosa* Roth) are sown into corn up to the V6 growth stage and allowed to exist under the corn canopy until harvest, when the cover crops begin to grow [60]. More research is needed to demonstrate consistent success in soybean and other crops in allowing an interseeded crop to persist through the growing season and into the winter. Precision seeding technologies are allowing innovations in relay cropping, where the life cycle of two cash crops overlaps within the growing season (e.g., soybean interseeded into wheat crop before wheat harvest). Crop-forage intercrop systems are emerging in Brazil, which allow soybean harvest followed by pasture establishment, with minimal effects on soybean yield, using *Brachiara* spp. [61–63]. Additionally, innovative corn growers in central Illinois in the United States are using precision seeding to create bio-strips and track-strips, where a bio-strip might consist of a mixture of radish, turnip (*Brassica rapa* subsp. rapa), oats (*Avena sativa* L.), forage pea (*Pisum sativum* L.), and buckwheat (*Fagopyrum esculentum* Moench), and a track-strip might contain sorghum sudangrass (*Sorghum bicolor* (L.) Moench ssp. drummondii), flax (*Linum* L.), sunflower (*Helianthus annuus* L.), sunn hemp (*Crotalaria juncea* L.), yellow sweet clover (*Melilotus indicus* (L.) All.), crimson or berseem clover (*Trifolium alexandrinum* L.), barley (*Hordeum* L.), triticale (*Triticosecale rimpaui* C. Yen and J.L. Yang), vetch, and rape (*Brassica napus* L.) (A. Reuschel, personal communication). Many knowledge gaps need to be addressed to improve performance and adoption of these practices; more information is needed on optimal timing for planting and termination of interseeded crops with cash crops and interactions with chemical pest management. Growers need information on which interseeded or intercropped and cash crop species provide the best yields and ease of management in combination.

3. Biological Weed Control

There are two approaches to biological weed control, whether the control agent is bacterial, fungal, insect, or other: classical biological control and inundative biocontrol [64]. Classical control relies upon the introduction of a pathogen, herbivore, or predator of the target pest. In order for classical biocontrol to work, there must be the appropriate environmental conditions for the biocontrol agent to survive and build a population. Persistent control may be possible [64,65]. Inundative biocontrol may be more amenable to agricultural systems, such as bioherbicides, which may be applied in similar ways to chemical herbicides, where insects, fungal spores, bacterial preparations, or inoculum may be applied [64]. Either approach may be useful in providing another approach to IWM.

3.1. Microbes and Viruses

Microbes may be used as bioherbicides in an innundative approach to biocontrol. To date, there is no microbial herbicide registered for use in agricultural crops, although there are products available for invasive weeds in natural systems [66]. Future innovation is predicted to be driven by herbicide resistance, lack of new herbicide sites of action, regulatory standards for herbicide safety and low toxicity, and public demand for non-chemical control methods [66]. Bioherbicides may be limited in their efficacy, providing only short-term residual effects, but may provide an additional selection pressure in an IWM system [67]. For example, bacterial species *Xanthomonas campestris* (strain LVA-987), may provide a new management option for horseweed (*Conyza canadensis* (L.) Cronquist) [68]. Most bioherbicides tested and marketed in the United States are species of fungi from three genera: *Colletotrichum* (ex. BioMal and Collego), *Phoma*, and *Sclerotinia* [64]. In addition to biological control using bacteria and fungi, viruses may also be bioherbicidal agents. The Tobacco Mild Green Mosaic Tobamovirus has been approved by the Environmental Protection Agency (EPA) for control of tropical soda apple (*Solanum viarum* Dunal) in pastures [64]. Additionally, relying on the principles of classical biocontrol using microbes, there is a current and growing body of research suggests that microbe-plant symbioses may help crop plants outcompete weeds. Some microbes, such as some species of arbuscular mycorrhizal fungi (AMF), may increase the crop competitive ability [69]. In a review of 304 studies, Lin et al. [70] found that the addition of AMF favored the competitive success of N-fixing broadleaf plants, suppressed C3 grasses, and had no effect on competitive ability of C4 plants, non-N-fixing broadleaves, or woody species. Root symbioses with AMF and rhizobial bacteria may improve crop nutrient availability, especially under low nitrogen or phosphorus availability [70–72]. However, there is the potential for AMF innoculation to benefit some species of weeds as well [70,73].

3.2. Animals

Seed predators can offer effective weed seedbank control if their required habitat is provided. Seed predation may account for up to 90% of seed loss [74]. Examples of animals that feed on weed seeds are voles (*Microtus* spp.), mice (Muridae), birds (Aves), earthworms, several species of ground beetles (Carabidae), and crickets (Gryllidae). The predators with the highest predation rates and abundance are ground beetles, consuming up to 1000 seeds m $^{-2}$ day $^{-1}$, and crickets [75,76]. There is a temporal aspect to predation rates, with highest activity in mid- to late-summer and tapering off in the fall, and there may be an interactive effect of other management practices, such as tillage, with the ability of seed predators to find seeds [77]. Seed predators have been shown to prefer complex habitats with cover from their predators, such as birds [78]. Therefore, there may be an interaction between cover crops and weed seed predators, since cover crops may provide complex habitat [79]. It is possible that predator populations are promoted by diverse cover crop mixtures or rotations, and more research is needed in diverse geographies and surrounding field habitats. Seed predation can also be promoted by creating corridors or habitat within the field; also referred to as a trap crop or beetle bank, this is a strip of vegetation within the field to provide overwintering habitat [80]. Field margins may provide the same basic function, to a lesser degree than beetle banks [80], but the land type of the habitat surrounding the field and the complexity of the landscape has been shown to influence the abundance of ground beetles [81,82]. Creation of seed predator habitat within the agricultural field may not be compatible with some crop management practices and chemical applications and may pose a challenge for pesticide applicator avoidance. Besides this, there is another major complication with negative interactions between beneficial insects and the use of some seed treatments [83]. Neonicotinoid and fungicide seed treatments have been shown to be a direct cause of mortality in Carabidae ground beetles [84], and seed treatments may have cascading ecological effects [83]. Integration of weed and seed predatory insects with robotics or precision agriculture systems could be a potential solution by depositing the insects in problem fields or locations within fields [85].

4. New (Currently Proposed) Solutions

4.1. Technological Advancements

A potential new technology is the use of RNA to silence key genes through the process of RNA interference (RNAi). This technology would potentially be applied as a spray to enhance weed susceptibility to herbicides or direct death of the weed. RNA has great potential for weed management, because sequences can be designed to selectively target a specific weed species or a group of related weed species. Presumably, targets of current herbicide chemistries could be inhibited, and there would be no cross-resistance with traditional herbicides, because RNAi works through a different mechanism. The commercialization of RNAi herbicides is not on the immediate horizon. There are several hurdles to implementation of this technology. First, the cost of RNAi herbicides on a large scale is high, although it is being reduced. Secondly, there are some technical problems with formulating RNA to readily be absorbed into the plant as spray. Also, there is uncertainty surrounding the registration of this technology in both how long it would take and public perception. The type of herbicide resistance mechanism will also impact RNAi use. Weeds with non-target site resistance mechanisms (herbicide metabolism or sequestration or reduced herbicide absorption or translocation) will be more difficult to control than weeds with target site resistance mechanisms, which may be the result of a mutation affecting the affinity of the herbicide to the enzyme binding site or may cause the overproduction of the targeted enzyme. Currently, there are few scientific sources on sprayable RNAi for weed management [86,87].

Clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR-associated protein 9 (CRISPR/Cas9) is a revolutionary approach to genetic editing that would, in general, pass a genetic element on to the progeny at a rate greater than the expected 50% from Mendelian inheritance [88–91]. Specifically, CRISPR/Cas9 could be used to introduce changes in the target species DNA. This genetic editing system efficiently inserts a targeted mutation, which results in a conversion from heterozygous to the homozygous condition and transmission of a specific gene to nearly all progeny. Practical applications of gene drive systems are not yet established, and population modeling is needed to determine feasibility of proposed approaches [92]. Genes could be introduced to lower the fitness of weed species through a gene drive system [91]. For example, dwarfing genes could be manipulated to create small-statured, less competitive weeds, or genes associated with reproductive development could be manipulated to reduce the number of offspring produced [91]. Hypothetically, HR weed populations could be altered to recover susceptibility to a given active ingredient [89], or highly conserved genes could be modified and sensitized to new herbicide molecules designed especially for the newly modified gene [91]. The modified genes would need to be functional, without fitness costs, to allow proliferation within the population. Weed species could also be genetically modified to improve control with other methods, such as HWSC. Neve [91] suggests the possibility of modifying the seed-shattering loci of black-grass (*Alopecurus myosuroides* Huds.) to retain seeds at harvest, allowing seed destruction. CRISPR/Cas9 is still a new technology with feasibility, regulatory, and ethical challenges. While there are applications in weed management, additional research is needed to guide this technological development.

4.2. Altering Sex Ratios of Amaranthus Spp.

Some species of flowering plants are dioecious, meaning there must be male and female plants present and subsequent gene exchange in order for reproduction to occur. In dioecious species, male-to-female sex ratios are expected to be expressed as 1:1, as long as costs of reproduction are not greater for one sex than the other [93]. Two of the most economically damaging weeds in corn-soybean rotations in the United States are dioecious plants: Palmer amaranth and common waterhemp. There is some suggestion that sex expression or the sex ratios of resulting offspring may be impacted by environmental factors [94]. Additionally, environmental stressors may impact male and female phenologies differently, leading to asynchronous flowering [95]. There is increasing interest in understanding the underlying mechanisms of sex expression in these species, in the hopes that sex ratios may be manipulated in the field [95,96]. Recently, male-specific markers were identified in Palmer amaranth and common waterhemp populations [97]. If a gene drive system could be developed to target sex-specific genes through CRISPR/Cas9, sex ratios could be managed to reduce the population [91,97].

4.3. Endless Possibilities

While the conversation of returning to the fundamentals of ecology has been initiated, it is important to note that some solutions, such as herbicide use, will continue to be an important part of weed management strategies. Herbicides are still effective, but should be used with caution to preserve effective herbicide sites of action [92,98]. Current research is incorporating herbicides and newer technologies, such as robotics and precision agriculture [48]. With this, there is new innovation in weed management. However, it is important that researchers and growers alike do not adapt or condone poor stewardship of these new management tactics. New technology must be used in an IWM approach to preserve utility for as long as possible.

As these new combinations of previous solutions and new technologies for weed management merge, it is important to note that there may be many options available relatively soon. For example, some tools that may be closer to commercial use than expected are spot and spray technology (i.e., H-Sensor (Agricon GmbH, Ostrau, Germany) and See and Spray (Blue River Technology, Sunnyvale, CA, USA)) [99], variable rate applications (both herbicides and irrigation) [100,101], autonomous tractors (concept vehicle by Case IH), targeted tillage [102], unmanned aerial vehicles [103], and robots that target weeds underneath the crop canopy [104–107]. More unique options that expand on weed recognition [108,109], which itself is still a work in progress, to complementary techniques include tactics, such as laser weeding [110,111], stamping [112], microwaves and radiations [113–115], electrical discharge [116], flaming [117–120], pressurized air [121,122], or solar irradiation [123–125], have been tested in the past and are being revisited in light of new technology. These technologies have begun to be incorporated into modern remote sensing systems. Further “outside of the box” ideas can be borrowed from other disciplines. A new biological control technique involves a drone that drops insects to feed on crop pests (Parabug [85]) or a mechanical robotic chicken tractor (UKKO Robotics [126]) that allows free-range chickens to be housed in an autonomous vehicle. While it is recognized that both of these are currently not being used in agronomic row crops or have been scientifically tested, they allow for a more ecologically driven approach to potentially combat weeds in a unique way. The National Aeronautics and Space Administration (NASA) is researching the possibility of agricultural production on Mars, where HR weeds would not be a problem [127].

While some commercial success has been demonstrated in smart-machine technology, there are several limitations: low weed and crop densities, growth stage and size, and planting pattern. New approaches are needed to identify weeds under moderate to heavy weed levels and when plant size is not a reliable means of weed detection. The current front runners for this are hyperspectral imaging and a crop-mapping sensor, via GPS, used at planting. Hyperspectral imaging methods for weed detection are more accurate under high weed densities because this method measures the reflectance spectra at each point in the image regardless of the visibility of the entire plant or leaf shape. The species identity is then determined for each point by spectral feature recognition rather than by shape analysis [128–130]. In addition to the method’s robustness to partial leaf coverage, Zhang and Slaughter [131] observed that the technique could reliably distinguish between closely related species, which could potentially overcome the challenge observed by Hearn [132] in distinguishing between species with similar leaf shapes. To have this technology be commercially available, a machine-learning approach would need to be implemented. Thousands of images of both weeds and crops would need to be digitally analyzed individually and then together to be able to distinguish them at varying growth stages.

An additional approach would be the use of a crop-mapping sensor that would map the planting locations and retain the information for further use by a weeding robot. The mapping of crops has been demonstrated by several researchers [133–136] by using GPS to centimeter accuracy. GPS equipment is already heavily used in agriculture, and the cost is likely to decrease with time and adoption. Therefore, researchers have only begun to scratch the surface of potential weed management tactics. While these options do not tackle weed management from an ecological perspective head on, IWM focuses more on the larger picture that will one day include some of these ideas. However, there is still a call to action for more ecologically driven weed management solutions, which researchers are beginning to answer.

5. Conclusions

Given current weed control issues, the future of weed control and ultimately food and fiber production are unclear. However, with advancements in ecological approaches, herbicides, and precision agriculture, there are new possibilities for the future that do not rely solely on the use of chemical control. Moreover, ecological interactions are not well documented and understood, and success of methods may rely heavily upon geographically-specific factors (soil type, OM, pH, climate and climate variability, species present, etc.). As such, there is a need for studies at all spatial scales, involving teams of multi-disciplinary researchers. It is also difficult to tease out the effects of varying management tactics in current long-term studies, which typically average about 3 years, especially in more complex systems. Truly long-term (greater than 3 years), field-scale studies are needed to examine the effects of IWM decisions. If available, historical data regarding grower decisions and management trends may be analyzed to elucidate effects of IWM or its components, as in Hicks et al. [98]. Furthermore, for ecological approaches to become widely accepted and understood by scientists and growers, there must be available research funding to focus on sustainable agriculture and ecological pest management systems. In order for there to be a focus on the research needed, government, industry, commodity, and non-profit groups will need to support research in weed ecology. However, there is reluctance to place funding on something that does not appear to be high priority or trending in research. When research funding is available, in order to make sense of complex data and to find trends in ecological relationships across geographies, data sharing should be encouraged by scientists and funding agencies.

Knowledge is still needed for the implementation of ecological practices in an IWM system at local, regional, and landscape levels, especially with the increasing complexity of management decisions. Some practices may be difficult or impossible to implement in certain geographies or with the available tools on the farm, but knowledge and some level of predictability must be gained. It is also important not to eliminate any options, which may be critical in building future weed management programs. This paper outlines current and future work that is needed from an ecological systems approach. Furthermore, the training of future weed scientists in the fields of ecology and biology in these systems is critical. While some other avenues of weed science may be more attractive to a new generation of weed scientists, the fundamentals and core of the discipline need to be valued.

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