Problems and perspectives in weed management

Donato Loddo,¹ J. Scott McElroy,² Vittoria Giannini³

¹Institute for Sustainable Plant Protection, National Research Council of Italy, Legnaro (PD), Italy;
²Department of Crop, Soil, and Environmental Sciences, Auburn University, Auburn, AL, USA;
³Department of Agricultural Sciences, University of Sassari, Sassari, Italy

Correspondence: Vittoria Giannini, Department of Agricultural Sciences, University of Sassari, viale Italia 39A, 07100, Sassari, Italy. E-mail: vgiannini@uniss.it

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Abstract

Despite the wide use of herbicides in the past century, their use is decreasing due to rising resistance phenomena, absence of discovery of new modes of actions and more regulatory restrictions. On the other hand, several tactics and technologies have developed recently providing alternatives from mechanical, cultural, robotic and natural products use perspectives, that could profitably enhance weed management within the agroecosystem and usher in a new paradigm of weed management that integrates chemical and non-chemical weed management practices.

In the next future, herbicide will remain an important tool for weed management and will be increasingly complemented by other innovative tactics and tools in a IWM perspective. This integrated approach would thus preserve the chemical and transgenic technology for future generations.

Introduction

Chemical weed control through the utilization of herbicides is the primary form of weed management in modern agriculture around the world. Since their progressive introduction in the 1940-50s, synthetic carbon-based herbicides significantly contribute to more efficient weed control, allowing a reduction of frequency and intensity of soil tillage operations and labor demand for weeding (Gianessi and Reigner, 2007; Gianessi, 2013). The availability of effective herbicides, particularly after the diffusion of herbicide-resistant transgenic crops, has facilitated the adoption of no-till agriculture practices across millions of hectares of cultivated land in North and South America reducing soil erosion and capture more carbon from the atmosphere to be stored in the soil (Bonny, 2008; Duke, 2015; Cerdeira et al., 2011). Given their efficacy as weed control tools, herbicides are the second most used group of pesticides, after fungicides in Europe. In EU-27, over the 2015-2019 period, herbicide sales reached an average of 130,000 tonnes per year, while fungicides and insecticides accounted for 160,000 and 40,000 tonnes per year, respectively (EUROSTAT, 2020). Despite the pivotal role played in modern agriculture over the past 80 years, sustainable herbicide use
is under threat in three ways. First, herbicide resistance is evolving around the world reducing the number of herbicide active ingredients available for use. Second, herbicide development has slowed with few if any new modes of action introduced in recent years. While herbicide resistance has been occurring for decades, the lack of new modes of action exacerbates the problem of herbicide resistance. Third, there is a change in public sentiment with respect to herbicide use around the world, some of which can be attributed to an excessive perception of herbicide risks compared to the actual ones, that has led in Europe to a stricter regulation in herbicide use. In this manuscript, we will discuss these three processes and also discuss the realities of development of new weed management technologies and tactics that could complement chemical-based weed management; thus preserving valuable herbicide technology.

**Herbicide resistance**

The evolution of herbicide resistance is progressively reducing the number of effective herbicides available for farmers. According to updated surveys, 521 unique cases of herbicide resistance have been recorded so far involving all the mostly used herbicides: 166 cases regarding resistance to Acetolactate Synthase inhibitors, 74 cases regarding triazines, 53 regarding glycines and 49 involving Acetyl CoA Carboxylase inhibitors (Heap, 2021). Herbicide resistance is strongly affecting weed management particularly after the spread of weeds with multiple resistance to herbicides with different Mode of Actions (MOAs). For example, in wheat growing areas in Europe the widespread presence of Acetyl CoA Carboxylase inhibitors (ACCase-inhibitors) resistant grass weeds, such as *Lolium* spp., has forced farmers to replace the once-predominant herbicides with Acetolactate Synthase inhibitors (ALS-inhibitors). However, after a few years of reliance on these latter herbicides, resistance has evolved also against ALS-inhibitors and weeds with multiple resistance are now common (Loureiro et al., 2017, Scarabel et al., 2020, Torra et al., 2021). Farmers then adopt other classes of herbicides to support or replace those that have reduced efficacy due to the evolution of herbicide resistance, entering in a continuous process of new herbicide use or combining new
herbicides that can be referred to as a “herbicide treadmill” following the concept of the “pesticide treadmill” (Foster and Magdoff, 2000).

Similar processes have occurred in many cropping systems worldwide, including also genetically modified organisms (GMO) cropping systems where the evolution of glyphosate and glufosinate resistance has made the first herbicide-tolerant varieties less effective against all weeds, necessitating that farmers use other herbicide MOAs in addition to glyphosate and glufosinate (Beckie, 2011). This has led to the introduction of novel GMO varieties with stacked herbicide tolerant-traits able to tolerate to a wider spectrum of MOAs, such as dicamba and carotenoid biosynthesis resistant crop varieties which has prompted again herbicide use changes but also promoted the further evolution of resistance against these additional MOAs (Beckie and Hall, 2014; Bonny, 2016), constituting a new process of intensification, the “transgenic or transgene-facilitated treadmill” (Binimelis et al., 2009; Mortensen et al., 2012). Weeds will adapt to any anthropogenic activity, including herbicides (McElroy, 2014) once they are subjected to repeated and constant disturbances provoking selection pressure. Utilization of herbicides along with non-herbicide weed management practices could have prevented or at least delayed resistance evolution thus, preserving valuable herbicide and transgenic technology.

**Herbicide research and development**

The loss of spectrum of herbicide effectiveness is worsened by the slowdown of herbicide discovery. No new herbicide sites of action (SOA) has been developed in the last decades (Duke, 2012) and only recently research activity and resource allocation in the herbicide discovery sector has increased, leading to the identification in 2018 of three herbicides possessing new modes of action (Umetsu and Shirai, 2020): cyclopyrimorate (site of action HTS, homogentisate solanesyltransferase, a downstream enzyme of HPPD) has been recently launched in Japan, tetflupyrolimmet (site of action DHODH, dihydroorotate dehydrogenase, an enzyme connected with de novo pyrimidine biosynthesis) is currently under development, and cinmethylin (site of action FTA, fatty acid
thioesterase, leading to the inhibition of fatty acid biosynthesis) has been approved in Australia. Nevertheless, no new herbicides with innovative SOAs will be commercialized in the next few years in most countries in the world (Kraehmer et al., 2014; Dayan, 2019).

The investments required to discover, develop and meet regulatory requirements for a new active ingredient have been progressively increasing (Bomgardner, 2011), representing therefore a strong deterrent for many companies to develop new chemical technology. More chemical compounds must be tested and evaluated to discover new and effective active ingredients than in the past since the most easy-to-find herbicide SOAs have been already discovered and fully exploited. Furthermore, more complex and costly toxicological and environmental studies are required to comply with the increasingly stricter requirements for the registration of a new active ingredient, particularly in the EU (Peters and Strek, 2008; Kraehmer et al., 2014). As a consequence, companies have preferred to develop and register new formulations or mixtures of old active ingredients, whose control efficacy and toxicity profile are easily predictable, instead of investing money in discovering new chemical classes of herbicides with new SOAs (Duke, 2012). Meanwhile, the rapid diffusion of GMO herbicide-tolerant crops in North and South America and Australia has contributed to limit for the last two decades the demand for new herbicides. Many farmers, who had previously used a range of diversified herbicides, after adopting GMO crops started relying almost exclusively on glyphosate (Bonny, 2008; Wilson et al., 2011). This caused a relevant reduction of the use of other herbicides in the main field crops (Nelson and Bullock, 2003).

**Pesticide regulation**

Pesticides are regulated by governmental agencies to evaluate the potential benefits and hazard of pesticides, and to aid in providing documentation on how to use pesticide products safely and effectively once registered. To illustrate the way in which the different countries assess pesticides we will compare the United States to the European Union.
**United States**

The Environmental Protection Agency is the regulatory body charged with the registering and regulating pesticide usage in the United States under the authority of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). The United States Environmental Protection Agency (USEPA) uses a risk assessment process in the evaluation of pesticides in the regulatory process (USEPA, 2021). Risk is the potential harmful effect of a pesticide for non-target organisms and the environment associated with a given level of exposure, that derives from its use under given technical and environmental conditions. All chemicals have potential risk associated with their use that must be quantified in the regulatory process and mitigated in pesticide labeling. Harm from possible risk can be reduced by using the pesticides in a way that reduces human and environment exposure. If risks exist, these risks are quantified in the registration process and mitigation strategies are implemented to reduce risk associated with pesticide use. The USEPA also conducts re-registration reviews of pesticides that take in new data, as well as public comment to provide continual assessment of pesticide safety.

**European Union**

The concern and awareness of alleged health risks and environmental impacts related to pesticide use has increased in European public opinion. The European Union therefore acknowledged there is public demand for an agriculture with lower pesticide use with the introduction of Regulation (EC) No 1107/2009 “concerning the placing of plant protection products on the market”. A two-step procedure has been adopted for the approval of new active ingredients or the renewal of approval of already-used active ingredients.

Firstly, a hazard-based assessment is conducted. Differently from risk-assessment procedure, hazard-based assessment of a pesticide considers only its intrinsic toxicity, that is the type and nature of adverse effects it may cause in an organism, without estimating the degree of exposure of that organism to the pesticide under conditions of field application. According to some “cut-off” criteria,
all pesticides containing substances considered of high concern for human health (e.g. carcinogens cat 1A, 1B) or for the environment (e.g. persistent organic pollutants, POP) are removed from the market. Once active ingredients are not discarded by the hazard-assessment, they are evaluated with a risk-assessment procedure to verify that they have, “consequent on application consistent with good plant protection practice and having regard to realistic conditions of use”, no harmful or unacceptable effects on human health, animal health, and the environment. The rationale behind Regulation (EC) 1107/2009 is to replace the old, more toxic active substances with newer and safer active substances or with non-chemical control methods; however, this has significantly reduced the availability of active substances for plant protection, with an estimated loss of at least 20% of active substances in the first years after the introduction of this Regulation and important effects on crop management since farmers can rely on fewer active ingredients, with the consequent greater risk of evolution of herbicide resistance if alternative non-chemical weed control tactics will not be adopted (Hillocks, 2012; Jess et al., 2014).

The future of weed management

Regardless of the reasons, agriculture could largely be living in or have recently lived through a period of “peak herbicide” -- a point of maximum herbicide usage for weed management. The constraints of herbicide resistance, lack of new herbicide development, and greater regulatory scrutiny could continue to erode the use of herbicides, as well as other pesticides. Herbicides have revolutionized weed management allowing humanity to grow more food and fiber on less land with less labor, and will continue to be the primary mechanism of weed management in the future, particularly for some cropping systems. However, a herbicides-dependent model requires a new paradigm for integrated weed management within agroecosystems to preserve herbicide technology and complement their efficacy.

An integrated weed management approach has been proposed for decades as a means of more sustainable weed management (see for example Barzman et al., 2015; Liebman et al., 2016) that will
also aid in the preservation of valuable herbicide and transgenic technology. What makes “today” different is simply that there is no longer a choice. With less herbicide active ingredients as described, farmers must utilize integrated practices to supplement or even substitute the use of herbicides. In the remainder we will discuss some of the most promising innovative tactics and technologies that could contribute to designing integrated weed management practices that could complement herbicide use. Many of these new technologies are in their infancy and their long-term impacts has not been realized. None of these practices are thought to be per se a definitive replacement for herbicides in the future but will function as a supplement or periodic alternative in integrated weed management scenarios.

Reducing broadcast applications

Herbicides are traditionally applied broadcast on the whole field surface, even on areas where they are not strictly necessary because no weeds are present or because other control methods are applied, as in the case of the inter-row of wide rows crops where mechanical weed control can be performed in addition to herbicide application. Different systems have been developed to reduce herbicide use by limiting their application only to field areas where weeds are present. Systems based on the combination of herbicide band application along the crop row and mechanical control in the inter-row have been proposed for different wide row crops, obtaining satisfactory weed control and crop yields with relevant reduction of herbicide use (Vasileiadis et al., 2016; Pannacci and Tei, 2014; Main et al., 2013). Further advances in the band application accuracy have become achievable with the diffusion of Real-Time Kinematic Global Positioning System (RTK-GPS) and auto-steering systems for the tractors and camera guided row-centering systems for the sprayers (Perez-Ruiz et al., 2013; Loddo et al., 2020). Similarly, ultra-high precision spraying systems have been developed with the integration of RTK-GPS positioning technologies, accurate cameras and optical sensors, image analysis and computer vision software, machine learning and very precise robotic nozzles. These systems, able to identify and distinguish single weed and crop plants and then apply herbicides only
on weed plants, have been used by different companies to create ultra-precise mounted sprayers (www.bluerivertechnology.com) but also autonomous, solar-powered robots (www.ecorobotix.com/en). Thanks to this extremely accurate targeted application, these systems are believed to reduce herbicide use up to 90-95% in comparison with broadcast application; however, this efficiency can be achieved only in fields with low to moderate weed density. These systems should be considered as an integration of other control tactics (chemical, cultural, mechanical); conversely, it is not recommendable to base the entire weed management solely on these systems.

Besides, some weeds species will likely evolve to mimic the appearance of desirable crops to thwart sensor technology as already occurred against other control tactics based on crop-weed discrimination. For example, *Echinochloa crus-galli* evolved to have a similar appearance to cultivated rice due to human hand-weeding selection pressure resulting in the evolution of the *E. crus-galli* ssp. *oryzicola* subspecies (McElroy, 2014). If species can evolve to confuse human eyes, it is possible for weeds to evolve to confuse sensor technology.

**Mechanical and physical weed management**

From mechanical perspective, the recent development of auto-steering machineries, equipped with optical sensors and RTK-GPS technologies to identify crop rows and hydraulic systems for real-time adjustment of tool positions, can improve weed control efficacy, reduce crop damage and significantly increase working speed and capacity in different wide-row crops (Kunz et al., 2018; Gerhards et al., 2020; Spaeth et al., 2020). Besides the low-tech mechanical devices such as cultivators, finger-weeders, brush weeders, and torsion weeders used in low density crops (Peruzzi et al., 2017), a series of alternatives have been presented by machines using heat for weed control both in pre-emergence and post-emergence phases. Indeed, soil steaming has proved to be a promising pre-emergence strategy killing most weed seeds, including dormant seeds (Kim et al., 2021); while in post emergence, heat could be used to control weeds through flaming (Rajković et al., 2021) and
microwave technologies (Khan et al., 2018), whose effectiveness is based on plant susceptibility to high temperatures determining the interruption of many biological and physiological processes. In addition to those technologies, cryogenic weed control has been also tested with promising effects (Cutulle et al., 2013). Moreover, as a response to the increasing diffusion of herbicide-resistant weeds, different systems have been developed to destroy weed seeds during crop harvest (Harvest Weed Seed Control). These systems, now commonly adopted in Australia, have shown promising potentials in reducing populations of important weed species, such as *Amaranthus palmeri* S. Wats., *Amaranthus tuberculatus* (Moq.) J.D. Sauer, *Chenopodium album* L., *Kochia scoparia* (L.) Schrad. or *Lolium rigidum* Gaud., across different cropping systems worldwide (Shergill et al., 2020; Walsh et al., 2018).

Increase mechanical activity in agricultural fields will have unintended consequences such as increased soil compaction due to increased entry of heavy mechanical equipment and increased burning of fossil fuels to power additional mechanical equipment. Mechanical weed management will not be a solution in all crops, only those crops that can be grown with specific row spacing and planting timings. Moreover, weed populations could shift to more perennial vegetation that is more difficult to physically remove or potentially damages desirable plants when removed (Fried et al., 2012).

Steaming, burning, microwave, and cryogenic practices will also be limited to specific crops that are more tolerant to possible damage from such practices. Human safety will also be a major hurdle to use of these practices as accidental exposure could be deadly to the applicator.

**Robotic weed management**

More recently, a new generation of robotic and automatic machines has provided not only quick weed identification in fields but also weed-targeted intervention (Steward et al., 2019), with possible in further update strategies able to fasten timing in weed emergence annotation and prompt management strategy, for example using a fleet of Unmanned Aerial Vehicles and Unmanned Ground Vehicles.
with complementary functions (Gonzales de Santos et al., 2017) and thus exploiting both ground detected and remote sensed data. In addition, autonomous weeding robots based on GPS/RTK technologies, such as Dino by Naïo-technologies (www.naio-technologies.com) or Robotti by Agrointelli (www.agrointelli.com), are already available on the market. Robotic weed management is likely years if not decades away from broad commercialization and adoption, especially for large-scale agronomic crops. There is still uncertainty about the economic benefits related to the introduction of weeding robots, considering both the initial investment and upkeep costs of robotic technology. Such technology will require a new skill set for farmers to service and maintain fleets of robot weeders.

**Cultural management**

From the agronomic perspective, over the well-known strategies concerning the selection of competitive cultivars, the optimization of seed density and fertilizers, there are several others crucially characterizing the design of the agro-ecosystems and that are driving a lot of attention. Among these latter, row configuration, distance between consecutive rows and management of inter-rows with living or mulching, relay intercropping can interplay with weeds for light, nutrients and water availability (Carlesi et al., 2020; De Vita et al., 2017). Underneath the agroecosystem design, the inter-row cultivation with plants able to produce allelochemicals can represent a strengthening tactic to suppress weeds (Jabran, 2017) as well as planning cover crops within the cropping system rotation which have demonstrated to furnish several ecosystem services (Adeux et al., 2021; Silvestri et al., 2021) especially when they are not intended as monocultures but as mixtures of different species (Ranaldo et al., 2020; Hefner et al., 2020). Recent studies have also underlined the importance of choosing, according to local agronomic and environmental conditions, the appropriate techniques for cover crop termination, such as chemical termination, roller-crimper or soil incorporation, to maximize weed suppression and beneficial effect on the following cash crops (Navarro-Miró et al., 2019; Frasconi et al., 2019; Alonso-Ayuso et al., 2020). Cover crops have been clearly demonstrated
to reduce weed populations, but not completely eliminate all weeds; thus, necessitating additional weed management practices such as herbicides.

**Natural chemicals**

Interest has been rising in essential oils, obtained by hydrodistillation or stem distillation from aromatic plants’ organs (Shaaban et al., 2012), that are mainly constituted by terpene hydrocarbons (monoterpenes and sesquiterpenes) or oxygenated compounds (phenols, alcohols, aldehydes and esters) and that have proved to have a ‘burning’ and thus ‘non-specific’ transient effect on many weeds (Jouini et al., 2020; Pouresmaeil et al., 2020). Given their high volatility, that could limit their fruitful use especially in organic farming, as well as their actual short shelf-life, promising attempts for their encapsulation with natural polymers such as arabic gum, starch, alginate and pectin are being tested. Indeed, safe nanotechnologies could enhance essential oils’ release properties and activities against unwanted organisms (Taban et al., 2020; Vurro et al., 2019), giving those products a marketability that do not yet have.

From the bio-based side, the exploration of natural resources for the identification of new active biocompounds is proceeding lively, with a particular focus on secondary metabolites. At this regard, some co-products of industrial vegetable oil production for bioenergy and green chemistry such as defatted Brassicaceae seed meal derived from seed defatting procedures and containing high levels of glucosinolates have shown suppressive effects against weeds (Matteo et al., 2018; D’Avino et al., 2015). To the big category of the bio-based products with herbicidal effects belong the fatty acids able to control a broad-spectrum of weeds and exhaustively represented by pelargonic acid, which is currently integrated in different marketed bioherbicides (Cordeau et al., 2016).

Given their herbicidal action only by contact, their use should be directed to the early weed seedling stage. Conversely, natural chemicals largely provide only temporary control of large annual or perennial weeds, thus necessitating multiple applications for acceptable control. Natural chemicals are largely non-selective in their herbicidal effect so desirable plants can be easily injured (Dayan et
al., 2011). Selectivity towards crops could be achieved through localized applications, thus avoiding the crop plants. Although natural, those products could present some hazard for the operators, thus risks related to their application should be taken into account.

**Final thoughts: a new paradigm**

In recent years, a series of tactics and tools belonging to mechanical, agronomic and bio-based approaches have been studied offering the possibility of developing case-specific integrated weed management (IWM) strategies with a cumulative impact on weed abundance and weed-competitive ability (Korres et al., 2019). In addition, IWM can rely on modern technologies, remote sensed data and robotics to control weeds (Lopez-Granados, 2011; Fennimore and Cutulle, 2019). IWM now has a diverse suite of tools and strategies that can be used to complement herbicides. Two decades ago, non-herbicide strategies for IWM were largely limited to cultural and mechanical practices. Moreover, farmers have to consider the current political and regulatory scenarios affecting the range of available tools and tactics for weed management. For example, the European Commission is increasingly asking for a consistent reduction of pesticide use as stated by the “Farm to Fork” strategy that imposes to reduce pesticide use by 50% by 2030 (European Commission, 2021). Regardless of weed management strategy used in the future, a new paradigm for weed management is on the horizon. This new paradigm will be one of reduced herbicide inputs and integration of non-herbicide management practices. Herbicides have been revolutionary tools and their full replacement by alternative weed management strategies would be not feasible in the next future. However, the combination of herbicides and alternative management practices will aid to design more sustainable cropping systems and to preserve valuable herbicide and transgenic technology.

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