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Review

Global Status of Herbicide Resistance Development: Challenges and Management Approaches

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Abstract: Chemicals are widely recommended for the suppression of weed in crop land. This paper attempts to a greater integration of ideas into the development of herbicide resistance. This may lead researchers to focus less on simply defining herbicide resistance and more towards comprehensive investigations of the resistance development. Weed expert in collaboration with plant biologists can work in synergy to come up with better approach and innovation aimed to curtain herbicides resistance challenges. Chemical herbicides exert undue pressure on weed fitness and the diversity of weed community's changes over time in response to both herbicides and other strategies imposed on them. Repeatedly and intensively, the regular application of herbicides with similar effect may swiftly result in population shifts to tolerant, difficult to suppress and ultimately result to weed community that is herbicide resistant, particularly in absence of using herbicides with different modes of action. Weed expert and evolutionary biologists have to work in synergy toward an improve and broader knowledge of plant resistant development. This collaboration is likely to proffer innovative solutions to the herbicide resistance challenges.

Keywords: Weed Fitness, Herbicide Resistance, Selection, Mode of Action, Diversity

Introduction

Herbicides are applied widely as a weed control tool in cropping systems across the globe. One major disadvantage of persistent application of herbicides has been the resultant development of herbicide resistance in weed species (Heap, 1999). It has been more than 50 years since Harper discovered resistance to herbicides (Harper, 1956). Herbicide resistance occurrences in weeds should be reduced, because it contributes greatly to the problem of food security globally (Busi *et al*., 2013). More recently, about 180 weed species has been identified to have developed resistance to herbicide application (Heap, 2007). Over the years there have been numerous publications on weed resistance to herbicides (Gressel, 2000; Powles and Shaner, 2001; Tranel and Wright, 2002; Delye, 2005; Powles and Yu, 2010).

The first occurrence of resistance was observed in wild carrot (*Daucus carota* L.), which developed resistance to the auxin analog class of herbicides after the herbicide had been used for several season (Switzer, 1957; Whitehead and Switzer, 1967). Since then, 362 weed cases of resistance have been reported in more than 180 species (Heap, 2011a). More than one-third of these species weeds have been detected in intensive arable crops (Heap, 2011b; Vencill *et al*., 2012). Ongoing herbicide selection in a wide cropping area on multiple populations of genetically diverse weeds has led and will continue to lead to further herbicide resistance development (Powles and Yu, 2010).

Some factors are responsible for resistance development, including the intensity of selection and the rate of occurrence of herbicide resistance genes. The first is easy to find out, but there is limited scientific knowledge linked to the first herbicide resistance development in weeds (Jasieniuk *et al*., 1996). For instance, *Lolium rigidum* is an important annual grass weed of cropping systems. Herbicide resistance emergence in L. *rigidum* was first discovered in 1980 (Heap and Knight, 1982) and now prevalent across more intensive cropping systems (Preston *et al*., 1999). In some places, over 40% of cropland is plagued with herbicide resistant L. *rigidum* (Nietschke *et al*., 1996). Many herbicide resistant collections of L. *rigidum* are simultaneously resistant to more than 12 herbicides representing seven Modes of Action (MoA) (Preston *et al*., 1996). Overall, all weeds that growers manage in an open field farm have the tendency to develop resistance to the practices used to manage them (DuPont, 2008). In this study, we summarize the main difficulties in the investigation of herbicide resistance to develop an integrated and more efficient weed management strategy.

Assessment of Herbicide Resistance Status

The conferment of resistance to herbicides in weeds is a gradually process that passes generation. Genetically, weed species are extremely diverse; the genetic differences within weed species include the intrinsic capability to withstand some chemicals. Nevertheless, the rate of occurrence of this genetic variation in a weed population is low. Between 2001 to 2005, about 12% of scientific research papers published in journals were relative with herbicide resistant weeds (Neve, 2007). Obviously, herbicide resistance is as important as the study of weed science. Herbicide resistance evaluations might be divided into three categories: Those that administer and determine resistance traits (characterisation); those that under sees the life science indicative of resistance (biological); and lastly those related to management of resistance (management). It is not astonishing to see that many of the early studies conducted on herbicide resistance intended to prove resistance development and to illustrate the biological and genetic basis of resistance traits conferment in weeds (Powles and Holtum, 1994). Consequently, one may conclude that scientists have become fixated with investigating resistance and less inclined to undertake research that synthesizes this information in order to achieve a more comprehensive understanding of the population biology of resistance (Neve *et al*., 2004).

On the other hand, farmers' have responded in various ways to herbicide resistance (Farmassist, 2006; Preston *et al*., 2006):

- The first response was not to worry about the problem: When it arrives, somehow we will solve it
- The next reaction was to begin applying herbicide mixtures or replace the current herbicide by more effective ones Often, farmers expect a magic solution to the problem (Storrie, 2006)

Herbicides resistant biotypes of 372 unique organisms were reported all over the world. The United States have 139, Australia has 60, Canada has 52, France and Spain each of them have 33, Brazil has 25, Germany has 26, the United Kingdom has 24 and about 1 to 19 was reported in most other countries as herbicide-resistant biotypes with intensive cropping systems. Each of these biotypes is resistant to at least one herbicide mode of action and numerous MOAs have chosen for a number of resistant weeds. About more that 100 weed species are resistant to the Acetolactate Synthase (ALS) inhibiting herbicides (e.g., chlorimuron, pyrithiobac, imazaquin) (Vencill *et al*., 2012). The main herbicide groups in which herbicide resistance has developed to date are the AC Case inhibitors, s-triazines and ALS inhibitors (Heap, 2006). Similar developments probably occur in the group of glycines and specifically glyphosate. Glyphosate resistance is particularly significant as it is a globally used highly effective herbicide, which controls weeds in crops, genetically modified or not (Powles and Preston, 2006). Since 1996, glyphosate-resistant crops have had a significant efficacy on agriculture, especially in the US, Brazil, Argentina and Canada (Brookes and Barfoot, 2011). In the United States, some species, including Palmer amaranth (*Amaranthus palmeri*), common water hemp (*Amaranthus rudis*), common ragweed (*Ambrosia artemisiifolia*), horseweed (*Conyza canadensis*), Italian ryegrass (Lolium multiflorum), rigid ryegrass (*Lolium rigidum*) and johnsongrass (*Sorghum halepense*), have developed resistance to glyphosate (Heap, 2009). Recently, many weed species have developed resistance to herbicides globally, especially in United States, where 156 weeds species have become resistant to a range of herbicide formulations Fig. 1.

Consequences of Overreliance on a Single Mode of Action

Although many factors contribute to the frequency of herbicide resistance events in weed communities, reviewing the reported incidents strongly suggests that the single most significant factor leading to the development of resistance is overreliance on one group of herbicides, all with the same mode of action, without using other weed management tools (Heap, 2011a). Rigid ryegrass and Italian ryegrass populations were identified where glyphosate had been applied for at least fourteen consecutive years (Perez-Jones *et al*., 2005; Simarmata *et al*., 2005).

According to Heap (2006), the main herbicides groups causing the serious problems of resistance are currently AC Case inhibitors, s-triazines and ALS inhibitors. Similar behavior is also indicated by the group of glycines, concretely glyphosate (Powles and Preston, 2006). Glyphosate-resistant horseweed (*Conyza canadensis*) and common ragweed had developed after continuous use of glyphosate on soybean (*Glycine max*) for three and six years respectively (Pollard *et al*., 2004; VanGessel, 2001). Additionally, glyphosate resistance in Palmer amaranth, horseweed, tall fleabane and other species was detected after some years of consecutive glyphosate application (Culpepper *et al*., 2006; Legleiter and Bradley, 2008; Travlos and Chachalis, 2010; 2013; Travlos *et al*., 2013; Urban *et al*., 2007). Herbicide resistance development is not limited to glyphosate., Hence, a large number of weed species both dicots and monocots are highly resistant to different herbicide groups with the various MoAs (Table 1).

The incidence of resistance in a weed population that was not previously exposed to the target herbicide is rare (Gressel and Levy, 2006; Gressel and Segel, 1990). The number of resistant individuals will swiftly increase with repeated use of the same herbicide or those with similar MoA. Beckie (2006) indicated that significant levels of resistance to ALS-inhibitor herbicides evolved in weed communities with as few as five applications. Combining recommended dose of various herbicide MoAs sequentially, or annually, greatly reduces the likelihood of individual plants resistant to a specific MoA to survive. In the majority of weed species, individual's naturally tolerance to more than one herbicide MoA will be rare (Vila-Aiub *et al*., 2013).

The Impact of Efficient Herbicide Dosage

In most countries, herbicides are the dominant method of weed control in crops. Consequently, where herbicides have been used intensively, there are many examples of the development of herbicide resistance (Heap, 2010; Powles and Yu, 2010). From an evolutionary perspective, many factors affect the dynamics of herbicide resistance under herbicide selection pressure. Despite the reported predominance of single gene Mendelian inheritance of resistance traits, Gressel and Levy (2006) have argued that reduced herbicide rates favors the development of quantitative resistance (Gardner *et al*., 1998; Gressel, 2002). One vital element in herbicide resistance development is the intensity of herbicide pressure, the major determinant of which is the herbicide application rate. Therefore, herbicides, when used at the proper plant growth stage and at the registered label-rate, cause very high mortality. For instance, herbicide use rates in Australia are often about 50% of that in other parts of the world (Bayer, 2010).

On 28% of the crop lands in Canada weeds are managed with reduced herbicide rates (Beckie, 2006). In addition to rate-cutting, environmental variability under field conditions and decay rates for residual soil herbicides can result in lower than label rates of herbicides being used on target weed populations (reviewed by Zargar *et al*., 2012; Zhang *et al*., 2000). Several studies on a range of crops and environmental conditions by Zhang *et al*. (2000) illustrated substantial variation in weed management efficacy from applying different herbicide rates (Zargar and Pakina, 2014). The same research indicated that weed control efficacy tended to be lower and more variable at reduced rates than recommended rates, but remained within the 60-100% range in over 90% of the cases. In many cases, weed control was over 70% at rates between 30 and 60% of the recommended rate (Zhang *et al*., 2000).

Weed control practices often combine herbicide application at reduced concentrations with other management techniques, to keep weed densities below economic threshold levels regarding to crop yield loss models (Blackshaw *et al*., 2006; O'Donovan *et al*., 2007). Although herbicide labeled doses are set sufficiently high to suppress a range of weed species across various growth stages, economically desirable weed control can often be obtained with below-labeled doses (Norsworthy *et al*., 2012).

Herbicide Resistance Costs

The cost in herbicide-resistant weeds has ecological and agronomic implications. In many developed countries, herbicide resistance results in higher short term costs to manage weed communities because herbicides are the primary means of weed management, particularly in the absence of new herbicide formulations. Recent studies have described the added costs related to the management of herbicide resistance weeds. It is usually expected that mutations conferring resistance to a novel stress will incur a fitness cost in the original stress free environment (Coustau *et al*., 2000). Also, it is well established that target site triazine resistance is accompanied by az substantial fitness cost in the absence of herbicide selection (Gronwald, 1994). Efforts to evaluate the costs related to herbicide resistance to other herbicide MoAs has been more equivocal, but, many of the published studies misinterpreted or mis-measured fitness costs.

On the other hand, resistance fitness and susceptible types have to be compared with a common genetic background. Researchers who compare resistance from various locations make little mention about resistance cost, because the genetic background is not restrained and disparity in growth and other limits factors can be due to genetic diversity that is of no significant for presence or absence of herbicide resistant weeds. Fitness itself should be examined from developmental stages (life cycle) in various environments, under antagonistic situations. Recently, some studies have been more observant in addressing these provisions (Roux *et al*., 2004; Vila-Aiub *et al*., 2005a; 2005b) which indicated a considerable cost of resistance. Therefore, it might be assumed that costs indicative for laboratory-acquired mutants can be distinguished from those derived in the open field.

Table 1. Herbicide resistant weeds by mode of action (www.weedscience.org)

Herbicide group	HRAC group	Example herbicide	Dicots	Monocots	Total
ALS inhibitors	B	Chlorsulfuron	97	62	159
Photosystem II inhibitors	C1	Atrazine	50	23	73
AC Case inhibitors	A	Sethoxydim	0	48	48
EPSP synthase inhibitors	G	Glyphosate	18	17	35
Synthetic Auxins	O	2,4-D	24	8	32
PSI Electron Diverter	D	Paraquat	22	9	31
PSII inhibitor (Ureas and amides)	C2	Chlorotoluron	10	18	28
Microtubule inhibitors	K1	Trifluralin	2	10	12
PPO inhibitors	E	Oxyfluorfen	9	1	10
Lipid Inhibitors	N	Triallate	0	10	10
Long chain fatty acid inhibitors	K3	Butachlor	0	5	5
PSII inhibitors (Nitriles)	C3	Bromoxynil	3	1	4
Carotenoid biosynthesis inhibitors	F1	Diflufenican	3	1	4
Carotenoid biosynthesis (unknown target)	F3	Amitrole	1	3	4
Cellulose inhibitors	L	Dichlobenil	0	3	3
Antimicrotubule mitotic disrupter	Z	Flamprop-methyl	0	3	3
HPPD inhibitors	F2	Isoxaflutole	2	0	2
DOXP inhibitors	F4	Clomazone	0	2	2
Glutamine synthase inhibitors	H	Glufosinate-ammonium	0	2	2
Mitosis inhibitors	K2	Propham	0	1	1
Unknown	Z	Endothall	0	1	1
Cell elongation inhibitors	Z	Difenzoquat	0	1	1
Nucleic acid inhibitors	Z	MSMA	1	0	1

*This table lists weeds species resistant to each site of action. Many species have evolved resistance to more than one site of action

The economic costs of herbicide-resistant weeds are a concern (Mueller *et al*., 2005; Boerbrom and Owen, 2006). Hence, two aspects will be illustrated: (a) The longer it takes to acquire resistance, the higher the cost of management. In this case, prevention is preferable. (b) If the herbicide to be replaced is less expensive than the new control plan, it is economically advisable to prevent the resistance. Many researchers have revealed that herbicide tolerance in valuable crop weeds results in economic losses (Pannell *et al*., 2004; Doole *et al*., 2009) this has been observed globally, especially in developed part of the world like Australia and United States. In the US, production cost of \$28.42 ha^{-1} in soybean enhanced because of glyphosate-resistant horseweed and, cost of handling glyphosate-resistant Palmer amaranth in Arkansas cotton production was computed at \$48 ha^{-1} (Vencill *et al*., 2012). Similar result about cost enhances in controlling glyphosate-resistant common water hemp in soybean was obtained by Legleiter *et al*. (2009). Moreover, the additional cost for controlling propanil and quinclorac resistant barnyard grass was calculated at \$64 ha^{-1} in Arkansas rice (Norsworthy *et al*., 2007).

Resistance Management Approaches

Although there is a considerable cost to manage herbicide defiant weeds, planters are often unwilling to carry out aggressive measures to minimise the risk of resistance development in their farms. A key element that adversely affects producer adoption of unsual procedure that will reduce herbicide resistance development is the anticipation of new herbicides availability in the future (Foresman and Glasgow, 2008; Llewellyn *et al*., 2002; Llewellyn, 2007). Studies are necessary to establish an integrated weed strategy as back-up to the dominant and often exclusive method of managing weeds with chemicals in field crops. Recent studies place emphasis on the need to investigate resistance studies within an evolutionary background. The application of evolutionary theorem to agricultural background is not new, but it is essential to appreciate and manage the effect of herbicide choices within a system perspective (Thrall *et al*., 2011).

Finnoff *et al*. (2007) indicated how managers who are cautious risk averse are less likely to adopt preventive measures because prevention only reduces the risk, rather than eliminating it. This perception is likely true for growers comparing the value of prevention control against the cost of herbicide resistance. However, in an illustration of more than 1000 corn, cotton and soybean growers in the United States, Frisvold *et al*. (2009) determined that using multiple herbicides with different MOAs was one of the least-adopted methods for herbicide resistance management, despite this practice being frequently identified by scientists as an efficient ways to reduce the risk of resistance development. The reason is that using diverse MoAs can increase short term weed control costs (Hurley *et al*. 2009), whiles the benefits of delaying resistance, accrue in the future and are more uncertain. In this regard, using different herbicide formulations with the different MoAs Fig. 2 is logically recommendation to control herbicide resistant weeds.

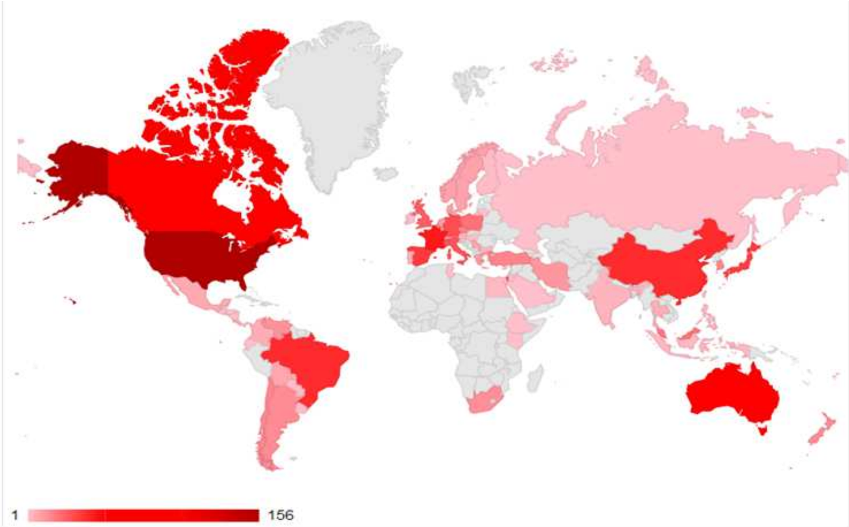

Fig. 1. The number of unique herbicide resistance all over the world (www.weedscience.org), Numbers of herbicide resistant weed species are displayed in graduated colours, the United States has the highest number of herbicide resistant weed species (156 species)

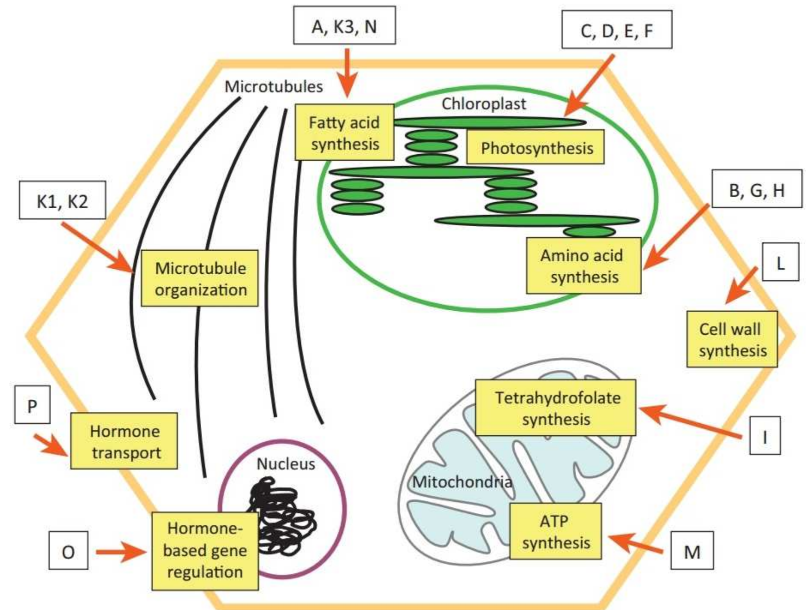

Fig. 2. Cellular targets of herbicide action and classification based on their mode of action according to the Herbicide Resistance Action Committee (HRAC). (www.weedscience.org)

Some growers believe that mitigating herbicide weed-resistant is beyond their control, depending more on their neighbor's behavior (Llewellyn and Allen, 2006; Wilson *et al*., 2008). Growers may also believe that industry will develop new formulations of herbicides, decreasing the benefits of resistance management (Llewellyn *et al*., 2002; Llewellyn, 2007). Alternatively, when using different MoAs provides short term returns comparable to current weed control strategies, farmers will be less certain about new, unfamiliar practices. Resistance management methods are naturally adopted reactively when a resistant weed species has become problematic and should be suppressed. Introduction of new herbicide resistance crop varieties can provide options for managing weed resistance to other herbicide MoAs, but desirable resistance management strategies must be adopted to avoid resistance emerging to the new herbicide as well.

Although the most favorable practice is to proactively use annual herbicide rotations and sequential applications before resistance evolves, that requires growers using multiple herbicides with different MoAs (Fig. 2) even if weed densities are low (Powles *et al*., 1997). More commonly, growers prefer to use one herbicide that still provides good control on susceptible weeds while adding a second herbicide to control resistant weeds. Jacquemin *et al*. (2009) indicated that applying mixtures to weed populations after resistance has evolved could be effective if the resistance mechanism imposes a significant fitness penalty via negative cross resistance. However, that scenario is not common. More research is required on the use of combined herbicide practices on already-resistant weed species, as well as on the potential for such methods to select for cross resistance (Preston, 2004).

Conclusion

Herbicides resistance development is globally a serious agrarian question in many agro-ecosystems. The important fact finding attempts in this field have to be towards the discovery of economically reasonable practices to prevent and manage herbicide resistant weeds. Herbicide-resistant crops have given growers economic and environmental benefits, involving time savings and reduced production costs as well as enhancing the opportunity to perform conservation-tillage approaches. Repeated herbicides application with the same MoA in herbicide-resistant crops has led to wide-spread herbicide resistance. The vast spectrum herbicides are also an answer to control weeds that had started to develop resistance to other herbicide MoAs. The majority of weeds studies have focused on predicting the probability of resistance development and the rate at which it will develop. Resistance prevention needs the adoption of combined weed management techniques, since one single control method cannot effectively and desirably eradicate resistant-weeds.

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Author's Contributions

Meisam Zargar: He is principal author and responsible for all research steps.

Han Eerense: He had a strong contribution in defining concepts and reviewed the manuscript.

Elena Pakina: She had a significant contribution in structuring issues on the paper, controlling abstract as well as in adjusting the paper template.

Tamara Astrakhanova: She supervised the draft manuscript and approved the final manuscript.

Tamila Ashurbekova and Saniyat Imashova: Helped in coordination, drafting and editing of the manuscript.

Engeribo Albert: He strengthened consistency of manuscript by controlling strictly the objectives and conclusion.

Hassan GI Ali: Coordinated the study and prepared the draft manuscript.

Eman Zayed: Supervised the draft manuscript and approved the final manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript.

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