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Dr. RR Upasani
Department of Agronomy, Birsa Agricultural University, Ranchi, Ranchi, Jharkhand, India

Dr. Sheela Barla
Department of Agronomy, Birsa Agricultural University, Ranchi, Ranchi, Jharkhand, India

Correspondence
Dr. RR Upasani
Department of Agronomy, Birsa Agricultural University, Ranchi, Ranchi, Jharkhand, India

Herbicide resistance in weeds it's Management

Dr. RR Upasani and Dr. Sheela Barla

Abstract
Resistance of weeds to herbicides is not a unique phenomenon. The first report of insects resistant to insecticides was in 1908, plant pathogens resistant to fungicides in 1940, and of weeds resistant to herbicides (Triazines) in 1968. Herbicides are considered to be among the most widely used pesticides. However, over-reliance on them and absence of any preventive or other cultural practices resulted to the evolution and spread of herbicide-resistant weeds. Development of herbicide resistant biotypes may be threat to successful crop production. Resistance to herbicides is a serious problem worldwide. The cases of resistance are increasing at an alarming rate. Cross and multiple resistances have further complicated the situation. Though arrival of new molecules with different mechanisms of action can help overcome present cases of resistance, an overreliance on chemical weed control will continue to give rise to cases of resistance. Therefore, alternate management strategies must be developed to combat resistance. Resistance management requires both preventive as well as reactive approaches. Prevention will include suitable combinations of weed management methods such as cultivation practices, crop rotations, field scouting and herbicide rotations. Seed production by suspected resistant biotype should be checked to prevent spread of resistance to other areas. Crop production programmes worldwide have been focusing on techniques and issues such as conservation tillage, sustainability of resources, resource use efficiency and most important of all, the changes in global climate. Therefore, integrated approaches involving judicious combinations of cultural, mechanical, biological and crop and herbicide rotations must be adopted to reduce the dependence on herbicides. Tillage method, planting time, method of herbicide application, optimum dose, stale seed bed and zero tillage are some of the short duration resistance management strategies. Allelopathic cultivar development could be another strategy to mitigate the herbicide load. Rapid resistant screening techniques should be developed which requires simple methods yielding quick results. Physiological and biochemical studies will be helpful to develop such screening techniques.

Keywords: Herbicide resistance, Biotype, Cross resistance, Multiple resistance

Introduction
Weeds are the major biological constraints in reducing crop yield. The competition is mainly for natural resources like nutrients, moisture and light which are responsible reducing quantity and quality of agricultural productivity Rao and Nagamani 2010, Rao *et al*. 2015. According to an estimate weeds in India reduce crop yields by 31.5% i.e. 22.7% in winter and 36.5% in summer and kharif seasons (Bhan *et al*. 1999). The following table reveals yield losses due to weeds in different crops.

Table 1: Potential yield loss due to weeds in different major crops of India (Rao *et al*. 2014).

Crop	Yield loss %	Crop	Yield loss %
Chieckpea	10-50	Pea	10-50
Cotton	40-60	Pearlmillet	16-65
Fingermillet	50	Pigeonpea	20-30
Greengram	10-45	Potato	20-30
Groundnut	30-80	Rice	10-100
Horsegram	30	Sorghum	45-69
Jute	30-70	Soybean	10-100
Lentil	30-35	Sugarcane	25-50
Maize	30-40	Vegetables	30-40
Niger '	20-30	Wheat	10-60

Thus it has been an established fact that weeds reduce farm yields and farm income drastically. So the introduction of pesticides in agriculture helped the farmers to control some of the noxious pests and thus reduced the yield loss caused by them at an affordable cost. Among all other weed control practices, herbicides alone are most effective and economically acceptable mean. Herbicides have revolutionized the weed management in world agriculture.

In the past three decades, evolution of newer herbicide molecules provided wider choice for the farmers (Duary and Mukhopadhyay 2004). Since the late 1940s, synthetic herbicides have been used in agriculture on a global scale to control weeds.

As in any perturbed biological environment, herbicide use has resulted in plant evolution and adaptation by the selection of genetic traits conferring phenotypic resistance (i.e., mechanisms protecting plants by a reduction in the herbicide damage) and allowing weedy plants to survive and reproduce in the presence of herbicides. Organisms are varied in sensitivity, responses and thus adaptability to such conditions and in responses to any treatment or imposed external factors. Tolerance and then gradual resistance of agricultural pests to any control method or environmental stress is thus a strategy through which organisms/ or pests encounter hazards and maintain life and therefore may be applied to any method of pest or weed control including prevention, mechanical, cultural, physical, biological and chemical (Qasem, 2003). For example, weeds resisting soil mulch cover show some morphological and/or physical characteristics that allow penetration of the mulch layer; also, flooding of resistant species possesses water impermeable seed coat or generates O_2 and reduces CO_2 penetration. Firing or flaming is resisted through presence of a hard seed coat or deeply buried regenerative propagules; certain weed species show feedback mechanisms or luxury accumulation of mineral nutrients and thus avoid toxicity; high temperature and low soil moisture harmful effects are avoided by adoption of secondary or enforced seed dormancy, while harmful effects of excessive light is avoided by some morpho-physiological alterations. Soil acidity may be encountered in the microhabitat by root exudates or selective mineral absorption and salinity by excretion of salt through different mechanisms and formation of salt glands or vacuoles or shedding salt saturated organs; microbes attack is avoided by production of repellent allelochemicals, and pests through some morpho-chemical adaptations (Maheshi and Larkin, 2017). However, the mechanism behind tolerance or resistance is different and based on the type of target pest or the hazard imposed.

Herbicides represent one of the external factors and form a group of synthetic- plus some bio-chemicals used to suppress or kill unwanted vegetation and are a major component of pesticides. They assist in management and restoration of areas invaded by invasive species. Herbicides are a major technological tool and responsible, in part, for an agricultural revolution and increase in food production in the last few decades. However, at present this technology faces radical changes in effectiveness under field conditions that lead in different cases to failure of weed control operation due to continued development of weed tolerance/resistance and evolution and limitations in the herbicide industry and development (Smith *et al*. 2005).

Herbicide resistance versus herbicide tolerance: Herbicide ***resistance*** is the ability of a weed biotype to survive an herbicide application, where under normal circumstances that herbicide applied at the recommended rate would kill the weed. In contrast, plant *tolerance* to a particular herbicide is the inherent ability of that plant species to survive and reproduce after treatment with that herbicide Gesine *et al* (2017) There are two general categories of resistance mechanisms, *target-site resistance* and *non-target-site resistance*. Target-site resistance inhibits herbicide action by: a change in structure of the target protein that decreases herbicide binding to its usual site of action; an increase in target protein expression; or an increase in copies of the gene containing the target site (Qian *et al*, 2016). Non-target-site resistance includes decreased translocation of an herbicide to its site of action, increased metabolic detoxification of an herbicide, and sequestration or immobilization of an herbicide in a part of the plant so it cannot reach its site of action. Herbicide tolerance in crops may be induced by techniques such as genetic engineering or selection of variants produced by tissue culture or mutagenesis.

Resistance of weeds to herbicides is not a unique phenomenon. The first report of insects resistant to insecticides was in 1908, of plant pathogens resistant to fungicides in 1940, and of weeds resistant to herbicides (triazines) in 1968. By 1991,120 weed biotypes that were resistant to triazine herbicides and 15 other herbicide families were documented throughout the world. Most herbicides inhibit specific enzymes in plants (target sites of action). Mutations in the target-site genes conferring functional enzymatic insensitivity to herbicides and subsequent target-site resistance (TSR) have been extensively reported (reviewed by Tranel and Wright 2002; Délye 2005; Powles and Yu2010).

Why worry about herbicide resistance?

Herbicides are considered to be among the most widely used pesticides. However, over-reliance on them and absence of any preventive or other cultural practices resulted to the evolution and spread of herbicide-resistant weeds. Development of herbicide resistant biotypes may be threat to successful crop production. Many herbicide options could quickly be lost for several crops if a weed biotype is resistant to more than one herbicide i.e. cross resistance (Jason, *et al* 2012). Obviously, a loss of herbicide options could have important economic and environmental consequences to agriculture. Also, in an era of high re-registration costs for older herbicides and high development costs for new herbicides, the possibility for replacement of the herbicides lost due to resistance diminishes. Finally, in most cases, it will not be easy nor inexpensive to assess resistant weed biotypes. Due to cross resistance, many resistance problems may have to be solved by trial and error, which could be quite expensive to the crop producer. The herbicide resistance issue does have solutions and perhaps the best place to start is to consider herbicides as a resource that needs to be preserved. Strategies for resistance prevention follow from there.

Resistance has increased rapidly since 1975, and today, there are currently 477 unique cases (species × site of action) of herbicide-resistant weeds globally. Herbicide-resistant weeds have been reported in 90 crops in 66 countries (Heap. 1997).The International Survey of Herbicide-Resistant Weeds (www.weedscience.org) reports 388 unique cases (species x site of action) of herbicide-resistant weeds globally, with 210 species. Weeds have evolved resistance to 21 of the 25 known herbicide sites of action and to 152 different herbicides. The ALS inhibitors (126 resistant species) are most prone to resistance, followed by the triazines (69 species), and the ACCase inhibitors (42 species). Herbicide-resistant weeds first became problematic in the USA and Europe in the 1970s and early 1980s due to the repeated applications of atrazine and simazine in maize crops. Growers turned to the ALS and ACCase inhibitor herbicides in the 1980s and 1990s to control triazine-resistant weeds and then to glyphosate-resistant crops in the mid 1990s in part to control ALS inhibitor, ACCase inhibitor, and triazine-resistant weeds. The massive area treated with glyphosate alone in glyphosate-resistant crops has led to a rapid increase in the evolution of glyphosate-resistant weeds. Glyphosate-resistant weeds are found in 23 species and 18 countries and they now dominate herbicide-resistance research, but have not yet surpassed the economic damage caused by ALS inhibitor and ACCase inhibitor resistant weeds. Lolium rigidum remains the world's worst herbicide-resistant weed (12 countries, 11 sites of action, 9 cropping regimes, over 2 million hectares) followed by *Amaranthus palmeri, Conyza canadensis, Avena fatua, Amaranthus tuberculatus, and Echinochloa crus-galli*. In the years ahead multiple-resistance in weeds combined with the decline in the discovery of novel herbicide modes of action present the greatest threat to sustained weed control in agronomic crops. The discovery of new herbicide sites of action and new herbicide-resistant crop traits will play a major role in weed control in the future however growers must make the transition to integrated weed management that utilizes all economically available weed control techniques (Ian Heap, 2012).

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Definition

Site of Action

Site of action refers to the biochemical site within the plant with which the herbicide directly interacts. Some herbicide site of action interactions are well understood, others are unknown. Many of the well-known sites of action are enzymes or proteins essential to plant growth and development **(Figure 1 and Figure 2)**. Also, some herbicides are believed to act at multiple sites.

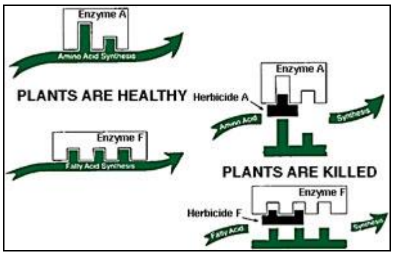

Fig 1.

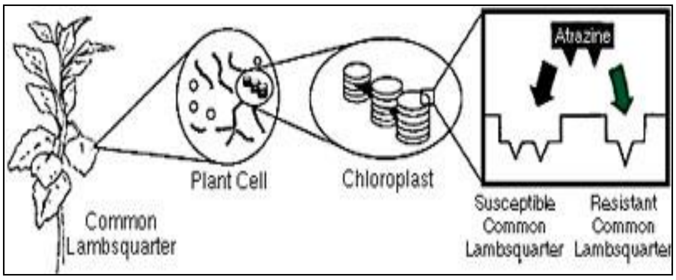

Fig 2.

Figure 1 Enzymes--Enzymes function as steps in biological processes. Enzymes are also extremely specialized in their function. As a result, many different enzymes are involved with the many different biological processes that occur within a plant. Some herbicides can stop specific enzymes from functioning, resulting in a disruption of specific plant processes; this often leads to the death of the plant. This herbicide-enzyme relationship is very specific and any chemical modification of the herbicide or enzyme can eliminate herbicidal activity.

Figure 2 Photosynthetic Inhibitors--The photosynthetic process occurs within a plant cell's chloroplasts. Certain herbicides can inhibit photosynthesis by binding to specific sites within the chloroplast. The relationship of a herbicide to the chloroplast binding site is very specific and any modification of the herbicide or binding site can eliminate herbicidal activity.

Metabolism: refers to the biochemical processes within the plant that generally modify herbicides to less toxic compounds. Differential rates of metabolism between crops and weeds are a primary method of crop selectivity to herbicides. One metabolic process may affect several different families of herbicides.

Herbicide families**:** These are a convenient way of organizing herbicides that share a common chemical structure and have similar herbicidal activity. Two or more herbicide families may affect the same site of action and therefore express similar herbicidal activity and injury symptoms.

A biotype

A biotype is a group of plants within a species that has biological traits that are not common to the population as a whole. For example, the Pursuit resistant corn hybrid Pioneer 3377 IR is a biotype of Pioneer 3377 and atrazine-resistant common lambsquarters is a biotype of common lambsquarters. Therefore, in most instances, specific biotypes are not easily recognizable by casual observation.

Selection intensity in regard to herbicide resistance is the degree to which weed control measures (e.g. herbicides) in a cropping system give a competitive advantage to a weed or crop biotype resistant to a particular herbicide.

Herbicide susceptibility means a particular weed or crop biotype is killed by the recommended use rate of the herbicide.

Herbicide resistance: Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.

Herbicide cross resistance: Refers to a weed or crop biotype that has evolved resistance to one herbicide that also allows it to be resistant to other herbicides.Example: weeds resistant to imidazolinone herbicides (Group 2, ALS inhibitors) are often resistant to sulfonylurea herbicides (Group 2, ALS inhibitors).

Herbicide multiple resistance: Refers to a weed biotype that has evolved mechanisms of resistance to more than one herbicide and the resistance was brought about by separate selection processes. For example, after a weed or crop biotype developed resistance to herbicide A, then herbicide B was used and resistance evolved to herbicide B. The plant is now resistant to herbicides A and B through two separate selection processes. Example: weeds resistant to both sulfonylurea herbicides (Group 2, ALS inhibitors) and glycines (Group 9, EPSP synthase inhibitors).

Herbicide tolerance: "Herbicide tolerance is the inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant."

How does selection of resistant weed biotypes occur?

Selection for change in weed populations begins when a small number of plants (a biotype) within a weed species have a genetic makeup that enables them to survive a particular herbicide application. Where this difference in genetic makeup originated is not clear. However, herbicides are not known to directly cause the genetic change (i.e. mutation) that allows resistance. The resistant biotype, therefore, is present in low numbers in natural populations and when a herbicide is applied, most of the susceptible weeds die but the few resistant weeds survive, mature, and produce seed. If the same herbicide continues to be applied and the resistant weeds reproduce, the percentage of the weed population that is resistant will increase (Figure 3).

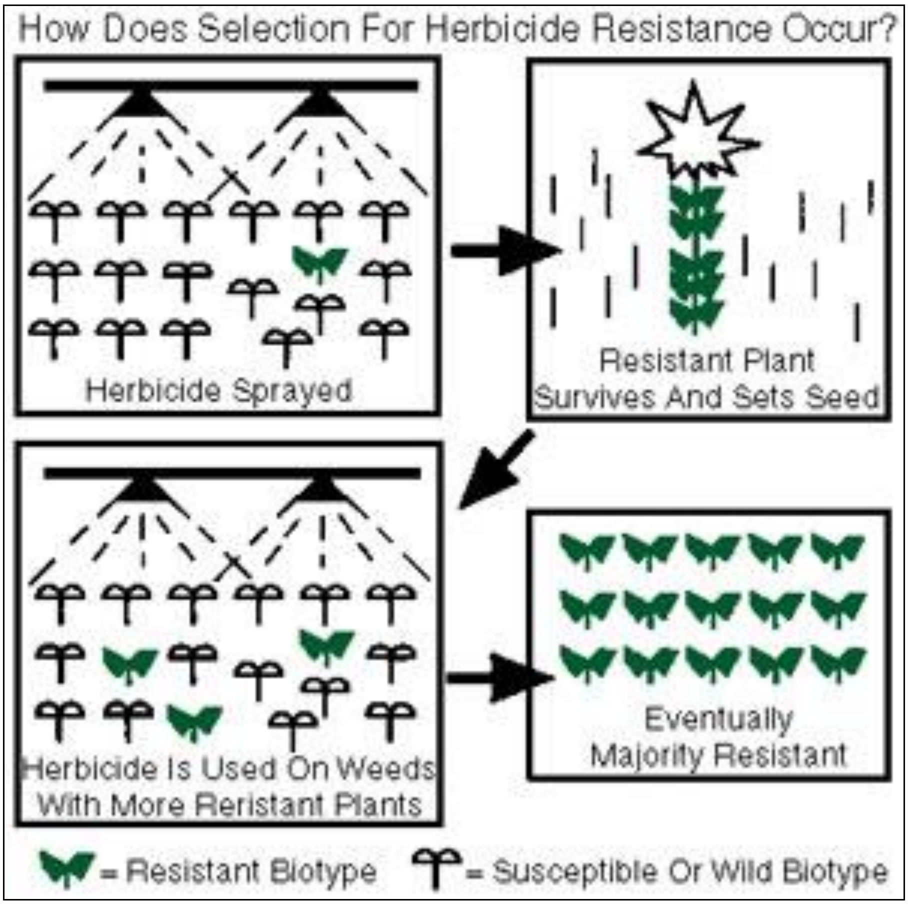

Fig 3: Selection for herbicide resistance begins when a herbicide resistant biotype survives a particular herbicide application. The resistant biotype survives, matures, and sets seed. If the same herbicide continues to be applied and the resistant weeds reproduce, eventually the majority of the weeds will be resistant to the herbicide.

The herbicide characteristics that affect herbicide resistance are as follows:

- Herbicides that act on a single site of action.
- Herbicides that are applied multiple times during the growing season.
- Herbicides used for several consecutive growing seasons or repeated application of herbicides with the same site of action to the same or different crops.
- Herbicides used without other weed control options (e.g. cultivation) and are considered "stand alone" weed control programs.

Status of Herbicide Resistance in India

Table 1: Herbicide resistant weeds

Herbicide Group	Mode of Action	Example of Herbicide	Total number of biotypes
ALS inhibitors	Inhibition of acetolactate synthase ALS	Chlorsulfuron	95
	(acetohydroxyacid synthase AHAS)		
Photosystem II inhibitors	Inhibition of photosynthesis at photosystem II	Atrazine	67
ACCase inhibitors	Inhibition of acetyl CoA carboxylase (ACCase)	Diclofopmethyl	35
Synthetic Auxins	Synthetic auxins (action like indoleacetic acid)	2,4-D	26
Bipyridiliums	Photosystem-I-electron diversion	Paraquat	24
Ureas and amides	Inhibition of photosynthesis at photosystem II	Chlorotoluron	21
Glycines	Inhibition of EPSP synthase	Glyphosate	14
Dinitroanilines and others	Microtubule assembly inhibition	Trifluralin	10
Thiocarbamates and others	Inhibition of lipid synthesis - not ACCase	Triallate	8
	inhibition		
Triazoles, ureas, isoxazolidiones	Bleaching: Inhibition of carotenoid biosynthesis	Amitrole	4
	(unknown target)		
PPO inhibitors	Inhibition of protoporphyrinogen oxidase (PPO)	Oxyfluorfen	3
Chloroacetamides and others	Inhibition of cell division (Inhibition of very	Butachlor	3
	long chain fatty acids)		

Carotenoid biosynthesis inhibitors	Bleaching: Inhibition of carotenoid biosynthesis	Flurtamone	2
	at the phytoene desaturase step (PDS)		
Arylaminopropionic acids	Unknown	Flampropmethyl	2
Nitriles and others	Inhibition of photosynthesis at photosystem II	Bromoxynil	1
Mitosis inhibitors	Inhibition of mitosis / microtubule	Propham	1
	polymerization inhibitor		
Cellulose inhibitors	Inhibition of cell wall (cellulose) synthesis	Dichlobenil	1
Unknown	Unknown	Difenzoguat	1
Organoarsenicals	Unknown	MSMA	1
Total Number of Unique Herbicide Resistant Biotypes			319

Modified from http://www.weedscience.org/Summary/MOA Summary.asp July 10, 2008

Table 2: Most common genera of weed developing resistance worldwide

Common name	Genus	Number of documented occurrence of herbicide resistance
Pigweed	Amaranthus	42
Lambsquarters	Chenopodium	25
Fleabane/Horse weed	Conyza	22
Ryegrass	Lolium	21
Foxtail	Setaria	17
Wild oat	Avena	15
Barnyard grass	Echinochloa	15
Black grass	Alopecurus	13
Groundsel	Senecio	12
Knot weed/Smart weed	Polygonum	12
Night shade	Solanum	11

Resistance risk assessment

For farmers to assess the risk of developing herbicide resistance, they need to evaluate their farming practices as well as the biology and herbicide susceptibility of their target weeds. The table below provides a checklist of resistance risk factors and can rank the risk of resistance development from LOW to HIGH.

Cropping System Evaluation - Risk of Resistance

Management Option	Low Risk	Moderate Risk	High Risk
Herbicide mix or rotation in cropping system	> 2 modes of action	2 modes of action	1 mode of action
Weed control in cropping system	Cultural*, mechanical and chemical	Cultural and chemical	Chemical only
Use of same mode of action per season	Once	More than once	Many times
Cropping system	Full rotation	Limited rotation	No rotation
Resistance status to mode of action	Unknown	Limited	Common
Weed infestation	Low	Moderate	High
Control in last three years	Good	Declining	Poor

**Cultural control can be by using cultivation, stubble burning, competitive crops, stale seedbeds, etc.*

Farming practices that increase the risk of resistance

- Frequent use of herbicides with a similar mechanism of action – this is the most important of all factors
- Monocultures and crop rotations that rely on the same herbicide mechanism of action for weed control
- Lack of non-chemical weed control practices such as cultivation, stubble burning, stale seedbeds and competitive and cover crops

Weed biology

- Density of weeds – more weeds means a higher chance of resistance
- Frequency of resistance in the population – greater genetic diversity means a higher chance of resistance
- Reproductive capacity – weeds that produce a high number of seeds can spread resistance more quickly

Management strategies for avoiding and managing herbicide resistant weeds

Resistance to herbicides is a serious problem worldwide. The cases of resistance are increasing at an alarming rate. Cross and multiple resistances have further complicated the situation. Though arrival of new molecules with different mechanisms of action can help overcome present cases of resistance, an overreliance on chemical weed control will continue to give rise to cases of resistance. Therefore, alternate management strategies must be developed to combat resistance. Resistance management requires both preventive as well as reactive approaches. Prevention will include suitable combinations of weed management methods such as cultivation practices, crop rotations, field scouting and herbicide rotations. Seed production by suspected resistant biotype should be checked to prevent spread of resistance to other areas. Crop production programmes worldwide have been focussing on techniques and issues such as conservation tillage, sustainability of resources, resource use efficiency and most important of all, the changes in global climate. Therefore, integrated approaches involving judicious combinations of cultural, mechanical, biological and crop and herbicide rotations must be adopted to reduce the dependence on herbicides. Tillage method, planting time, method of herbicide application, optimum dose, stale seed bed and zero tillage are some of the short duration resistance management strategies. Allelopathic cultivar development could be another strategy to mitigate the herbicide load. Rapid resistant screening techniques should be developed which requires

simple methods yielding quick results. Physiological and biochemical studies will be helpful to develop such screening techniques.
Use herbicides only when necessary. Where available, herbicide applications should be based on economic thresholds.
Rotate herbicides. do not make more than two consecutive applications of herbicides with the same site of action to the same field unless other effective control practices are also included in the management system.
Apply herbicides in tank-mixed, prepackaged, or sequential mixtures that include multiple sites of action.
Rotate crops, particularly those with different life cycles
Combine, where feasible, mechanical weed control practices such as rotary hoeing and cultivation with herbicide treatments
Clean tillage and harvest equipment before moving from fields infested with resistant weeds to those that are not.

Conclusions

Herbicide use is increasing dramatically in different crops and this trend is expected to continue. Continuous use of the same herbicide or herbicides having same mechanism of action in mono culture with minimum tillage has been the major causes of occurrence of herbicide resistance. Herbicide *per se* does not cause any mutation resulting herbicide resistance. Weeds with a diverse genetic background may have resistant biotype within a large population. Repeated use of same herbicide over several seasons in a same area exerts selection pressure on resistant individual to evolve. Herbicide-resistant (HR) weed populations are evolving rapidly as a natural response to selection pressure imposed by modern agricultural management activities. Continuous use of the same herbicide or herbicides having same mechanism of action in mono culture with minimum tillage has been the major causes of occurrence of herbicide resistance. It is only through the development and implementation of an integrated weed management program utilizing as wide a variety of weed control practices as are economically feasible that the problem can be effectively managed or prevented. Mitigating the evolution of herbicide resistance depends on reducing selection through diversification of weed control techniques and eliminating additions of weed seed to the soil seedbank. Effective deployment of such a multifaceted approach will require shifting from the current concept of basing weed management on single-year economic thresholds.

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