# Management of herbicide-resistant weed populations

## 100 questions on resistance

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## Abbreviations

| | |
|---|---|
| **CASAFE** | Camara Argentina de Sanidad Agropecuaria y Fertilizantes, |
| **CIAFA** | Cámara de la Industria Argentina de Fertilizantes y Agroquímicos |
| **CPRH** | Committee on Prevention of Herbicide Resistance |
| **CRC** | Cooperative Research Centres |
| **EEAOC** | Estación Experimental Agroindustrial Obispo Colombres |
| **EPPO** | European and Mediterranean Plant Protection Organization |
| **EPSPS** | enzyme 5-enolpyruvylshikimate-3-phosphate synthase |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **HRAC** | Herbicide Resistance Action Committee |
| **WAHRI** | Western Australia herbicide Resistance Initiative |
| **WHRAG** | Weed Herbicide Resistance Action Group |

## Preface

Herbicides are good tools for effective weeding. The use of these chemicals enables farmers to safe labour of three or four hand weeding in any annual or perennial crop. Herbicide application has also enabled farmers to grow major food and industrial crops, such as rice, wheat, maize, fruit orchards, sugar cane and several others in large areas in several countries of the world.

Despite all these benefits, misused inappropriately used herbicides can become a serious problem for the farmer and society. Every chemical substance used in agriculture can cause a negative effect to the environment if improperly applied or used at high rates. The prolonged use of the same herbicide can cause problems of herbicide resistance, a phenomenon consisting in the selection of resistant population of a weed previously fairly well controlled by the same herbicide.

Herbicide resistance is defined as the natural inherited ability of a biotype within a population to survive and reproduce after a herbicide application to which, under normal conditions, the original population was susceptible. The selection pressure of the herbicide over the resistant population increases with longer and frequent use of the herbicide, resulting in the selection of resistant biotypes.

In the last three decades, the number of cases of herbicide-resistant weeds has increased considerably worldwide. Although it is a known problem, farmers in many countries detect the problem of herbicide inefficacy when the resistance is already in the field; even worse, sometimes they stop using other herbicide ingredients that have the same mode of action as the one previously used, which aggravates the problem. The biotypes of resistant weeds become a more serious problem than the weed itself, since they are pests of increased hazard due to the difficulty in eliminating it.

To give an idea of this phenomenon globally, the international database on herbicide resistance (www.weedscience.org/in.asp) reports more than 310 resistant biotypes and 183 resistant weed species. The total area affected, although not estimated, may cover several thousand hectares of crops regularly treated with herbicides in countries as Australia, Canada and the

United State of America, as well as countries in the European Union and South America.

There is accumulated experience of several cases of resistant weeds to a great variety of herbicides. This necessary information should be compiled as a basis for future work in preventing this problem in other locations, countries and regions.

The best resistance management is through prevention, using economically and technically effective strategies. Effective prevention is one that is able to reduce the problems of selection pressure.

At the same time, in practice, the main way to understand and avoid the problem consists in detecting possible resistance through regular assessment of fields treated with herbicides.

This book has been prepared by Andreu Tabernet Palou (Servicio de Sanidad Vegetal, Unidad de Malerherbología, Generalitat de Cataluña, Lleida, Spain), Alicia Cirujeda Ranzenberger and Carlos Zaragoza Larios (Centro de Investigación y Tecnología Agroalimentaria, Gobierno de Aragón, Zaragoza, Spain), who are involved in studies and actions on resistance prevention and management. It is an important contribution and guidance for agricultural extension workers on herbicide resistance prevention. The material carefully describes the activities to be carried out by personnel working with farmers and the strategies to implement for preventing and managing resistance. The application of these lessons learned by specialists on this issue may help towards a better use of herbicides in general and the avoidance of its resistance.

Aware of the problems of herbicide use and resistance, the Food and Agricultural Organization of the United Nations (FAO) offers this document to all stakeholders, particularly technicians and specialists in developing countries, in order to facilitate the implementation of improved strategies for weed management.

# 1. INTRODUCTION

## 1.1 Interests and Objectives

Resistance of weeds to herbicides is an undesirable secondary effect produced after the repeated use of a single herbicide, where a weed population is no longer controlled with the same efficacy by a herbicide which, in normal conditions in a particular crop, had been effective against the weed population.

Herbicide resistance implies the reduction of the use of a certain herbicide, which should be replaced by another herbicide or by another non-chemical control strategy, in order to maintain the adequate level of control of the weed in the field.

Since farmers generally use the most effective and the least expensive herbicide, resistance involves cost increases (Orson, 1999; Preston *et al.,* 2006). Thus, prevention is seen as an obligatory measure to if one wishes to have the best control strategy for a longer period of time.

Resistance prevention requires adopting an integrated weed management approach, since no single control strategy can effectively and sustainably eliminate resistant weeds (Storrie, 2006).

Resistance, however, has generated positive aspects (Owen, 1997). It is vital to have better knowledge of weed species biology (Sans and Fernández-Quintanilla, 1997) and of herbicides (Mallory-Smith and Retzingher, 2003) and other control strategies for the adoption of integrated weed management (Catizone and Sattin, 2001).

This publication aims to review the main concepts and issues related to herbicide resistance for implementing better weed control strategies.

To this end, there are different initiatives that can be valuable in herbicide resistance. In addition, there are books that comprehensively deal with the problem of resistance, particularly the recently published Powles *et al* (Powles *et al*, 2006).

Some examples, without being exhaustive, are:

- Herbicide Resistance Action Committee (HRAC, 2006) webpages provide abundant information updated regularly;
- Heap (2006) maintains the website www.weedscience.com, a database on herbicide resistance, which exhaustively collects updated data on herbicide resistance from various countries. It also includes an updated bibliography on each herbicide-resistant weed;
- Weed Herbicide Resistance Action Group (WHRAG, 2006), based in England, offers information and technology on the herbicide-resistant *Alopecurus myosuroides*;
- Cooperative Research Centres (CRC, 2006), based in Australia, aims at herbicide resistance management of *Lolium rigidum*;
- Western Australia herbicide Resistance Initiative (WAHRI, 2006), also Australian, is an institution devoted to prevention and management of herbicide resistance. It provides excellent data on resistance on its website: www.wahri.uwa.edu.au];
- Beckie (2006), a Canadian publication, provides a good review of strategies and practices for management resistant *Lolium rigidum* & *Avena* sp;
- in the United States, there are various materials on transfer technology, such as bulletins from agricultural extension services providing good information on herbicide resistance;
- the National Glyphosate Sustainability Working Group (2006) deals comprehensively with the problem of resistance derived from the use of glyphosate and recommends actions to take in resistance prevention and management.

Previous FAO publications on weed management such as FAO (1997 and 2001) as well as Valverde (2004), which focuses on this problem in developing countries.

All of this information is mainly related to annual weeds. However, there are also some sources of information on perennial weeds, such as *Sorghum* *halepense*: Colquhoun (2001), Rakesh (2004a and 2004b), Estación Experimental Agroindustrial Obispo Colombres (EEAOC 2006) and Camara Argentina de Sanidad Agropecuaria y Fertilizantes, (CASAFE)- Cámara de la Industria Argentina de Fertilizantes y Agroquímicos (CIAFA) (2006). All of the above should be consulted since they provide good descriptions on what to do in case of new problems of resistance. Even with a great deal of information, however, farmers and herbicide agents have enormous difficulty in obtaining this information and data, which are necessary for preventing herbicide resistance and for adopting integrated weed management programmes.

For this reason, this publication provides working material and information addressed mainly to extension agents and farmers to help them manage herbicide resistance.

Accordingly, as a compendium, the aspects developed in this publication are as follows:

- a description of various methods for detecting herbicide resistance in the field and in the laboratory;
- methods for managing herbicide-resistant populations, either using herbicides or non-chemical control strategies, including mechanical and cultural methods;
- emphasis on economical aspects for preventing resistance;
- methods for technology transfer on herbicide resistance prevention and management.

This material aims at providing effective assistance to farmers to adopt a positive and pro-active response to new cases of herbicide resistance, rather than wait until the resistance develops. To this end, several questions were prepared on all aspects relating to the problem of herbicide resistance.

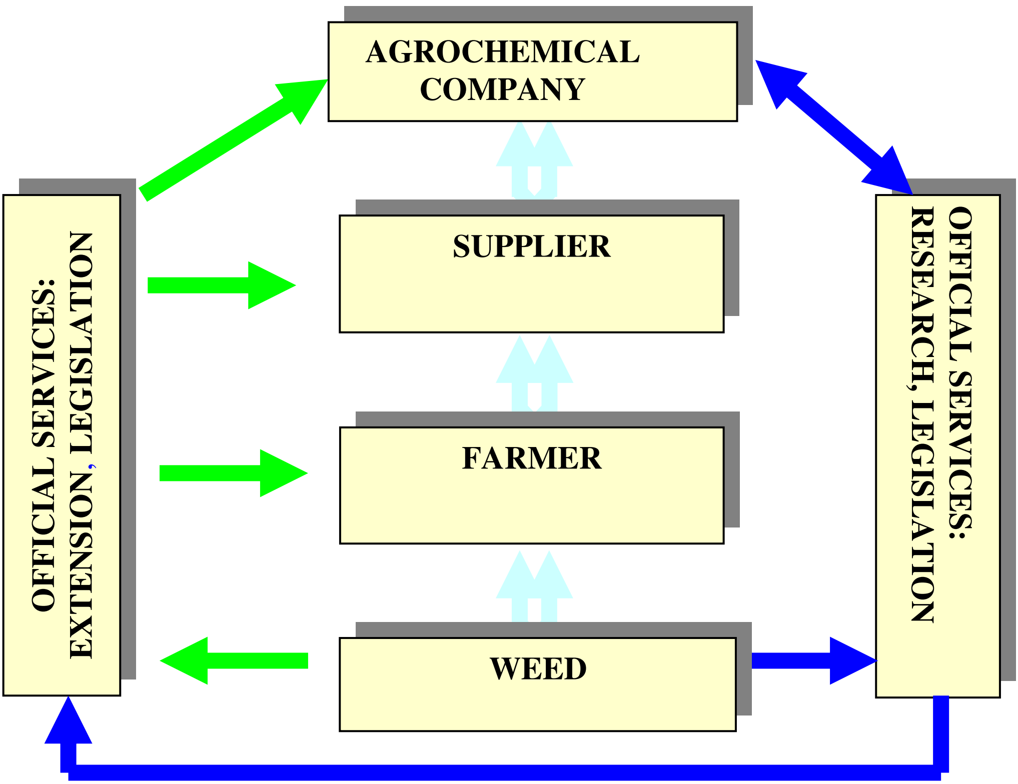
| |
|---|
| *Herbicide resistance affects all.* |
| *The farmer and the herbicide agent can prevent resistance with a proactive attitude.* |

### 1.2 To whom is this publication useful?

This publication is aimed at actors involved in the process of herbicide resistance management, especially in developing countries, to raise awareness on the need to efficiently control weeds and on the need to efficiently control weeds should one continue to have a very useful tool in weed management.

There are different main actors involved in this issue with different interests, but all with the common objective of achieving an adequate level of weed control. The main actors are shown in Figure 1.

**Figure 1: Levels of participation in weed control that should be coordinated for good herbicide resistance prevention and management**



This issue of coordination is important for groups working on herbicide resistance prevention and management. It provides the guidelines towards achieving this goal and the coordination among them.

## 1.3 Importance of herbicide resistance

The practical implications of herbicide-resistant weeds affect farmers because of derived complications in carrying out an appropriate control programme and the need to abandon the use of certain herbicide active ingredients that were effective in the past. These control tools are often the optimal cost-effective options. Herbicide resistance also affects farmers since they cannot efficiently establish the desired crop and are even forced to abandon it in order to prevent the presence of the resistant weed biotype.

Resistance is also of concern for enterprises producing and/or distributing the herbicides.

In both cases, the commercial life span of a product causing the resistance cannot be extended nor its effectiveness guaranteed. The herbicide stops being effective against a particular weed species but not for all populations of other species. In some cases, there are weed populations still susceptible to the herbicide and the farmers continue using it, but predictions on its efficacy are inaccurate. To solve this problem, it is necessary to use other herbicides or to adopt other control strategies, which are always the priority of the farming business.

Resistance also affects the herbicide registration process, since it generates the need to justify the herbicide prevention (European and Mediterranean Plant Protection Organization (EPPO), 2002) with its consequent technical and economical complications.

Farmers' responses to the problem of herbicide resistance are various (Monsanto, 2006; Farmassist, 2006; Preston *et al.*, 2006):

- the first response is not to worry about the problem: "*when it arrives, somehow we will solve it.*" In the meantime, they continue to use the same herbicide due to its low cost, increasing the rates of application.

- the second response is to start using herbicide mixtures or replace the current herbicide by more effective ones.

Sometimes, the farmer expects to have a magic solution to the problem (Storrie, 2006), hoping that it can be solved by using a new herbicide. This way of thinking is wrong. As stressed in study, the solution will come by adopting an integrated management approach consisting of various components of herbicide use and crop management.

*There is excellent information that provides guidelines to follow:*

- *Books and scientific papers*
- *Bibliographical reviews*
- *Pamphlets on herbicide resistance*
- *Bulletins*
- *Web pages:* *www.weedscience.com*
  *www.plantprotection.org*
  *www.weeds.crc.org.au*
  *www.pesticides.gov.uk*

## 1.4 What is a resistant weed?

In weed resistance to the herbicides, some useful definitions should be clarified, which are helpful in differentiating cases of resistance from cases of low herbicide efficacy. Accordingly, the definitions given by the Spanish Committee on Prevention of Herbicide Resistance (Comité de Prevención de Resistencia de Herbicidas - CPRH) (Chueca *et al.*, 2005) should be taken into account.

First, what is weed **resistance**? It is the inherited ability of a plant biotype to survive the application of a herbicide, which had originally been effective against that weed population.

Susceptible weeds must be distinguished from tolerant ones. The **susceptible** weed is a weed biotype that is unable to survive the application of a herbicide at its normal rate. The **tolerant** or **unsusceptible** weed is a biotype that has never been affected by the use of a herbicide.

*Herbicide resistance must be seen from the agronomical point of view.*

- *A weed in a crop that is initially easily controlled by applying a determined herbicide rate is no longer controlled by the same herbicide, much greater effort is needed to control it or it will not be able to be controlled by the herbicide alone.*

In these definitions, the concept of **biotype** is taken into account, which is the group of plants of a species with a common trait. In this case, it could be the susceptibility or the resistance to a herbicide which differentiates one biotype from the rest of the plants of the same species.

A **weed population** is a group of individuals of a species that invade a field.

### 1.5 Main species affected by problems of resistance

To date, the number of resistant weeds is high. This situation can be well followed by regularly consulting the relevant database in www.weedscience.com (Heap, 2006).

With regard to the magnitude of this phenomenon and its worldwide distribution, it should be stated that in 2006 there were 311 resistant biotypes from 183 species, including 110 dicots. and 73 monocots., which affect approximately 270 000 fields.

**Figure 2: Worldwide distribution of herbicide resistant weeds[1]**

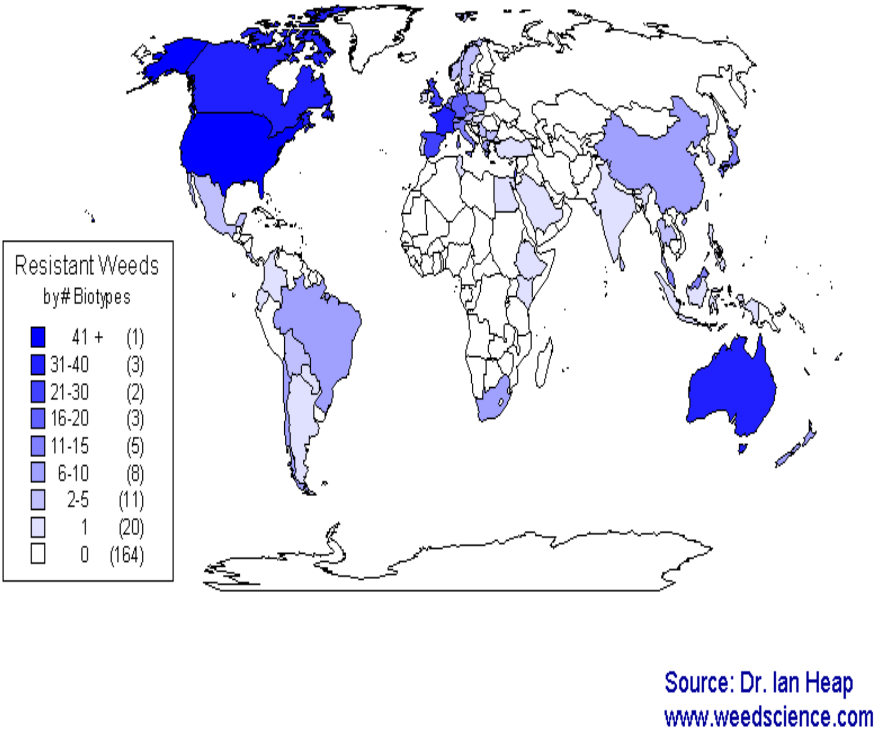



Figure 2 shows the worldwide distribution of resistant biotypes in Australia, Europe and North America, geographical regions severely affected by this problem. However, some areas of Africa, China and South America are also affected. Efforts to disseminate all this knowledge to prevent resistance are thus fully justified.

The ten weed species facing problems of herbicide resistance are shown in Table 1 (Heap, 2006).

[1] Note: Different colours indicate the number of resistant biotypes in each country

| | ***Species*** | ***Common Name*** |
|---|---|---|
| *1.* | *Lolium rigidum* | Vallico |
| *2.* | *Avena fatua* | Wild oat |
| *3.* | *Amaranthus retroflexus* | Pigweed |
| *4.* | *Chenopodium album* | White pigweed |
| *5.* | *Setaria viridis* | Cola de rata |
| *6.* | *Echinochloa crus-galli* | _____ |
| *7.* | *Eleusine indica* | _____ |
| *8.* | *Kochia scoparia* | _____ |
| *9.* | *Conyza canadensis* | Coniza |
| *10.* | *Amaranthus hibridus* | Pigweed |

Source: Heap, 2006

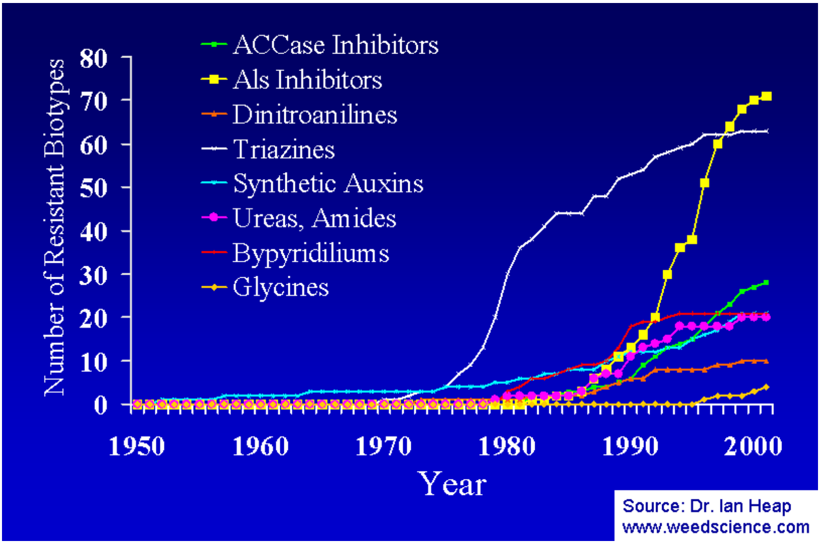
**Table 1: Ten major weeds affected by herbicide resistance**

## 1.6 Main herbicides causing problems of resistance

According to Heap (2006), the main groups of herbicides causing the most problems of resistance are currently the ACCase inhibitors, s-triazines and ALS inhibitors. Similar behaviour is also shown by the group of glycines, concretely glyphosate (Powles and Preston, 2006).

Glyphosate resistance is especially important as a highly effective compound due to its worldwide use, and due to the serious problems that its resistance may cause in the management of genetically modified crops.

**Figure 3: Main herbicide groups causing resistance**




*Herbicide resistance is largely spread in several agricultural areas of the world.*

*Nearly all herbicides have resistant weed populations, particularly s-triazines, ACCasa inhibitors (sulphonyureas) and ALS inhibitors (fops, dims). Glyphosate, the most used herbicide, is also affected by resistance.*

Figure 3 shows that a few years after beginning herbicide use, cases of herbicide resistance have been documented, mainly related to synthetic auxins.

## 1.7 Economic aspects of resistance

Do herbicide-resistant weeds affect the farmer economically? What is more economical, preventing resistance or managing it once it emerges?

The economic aspect of resistance is always a cause for concern (Orson, 1999; Mueller *et al.*, 2005; Boerbrom, 2006). Two aspects should be considered:

- if the resistance takes a long time to evolve, the cost of prevention will be high. In any case, prevention is always the best option;
- if the herbicide to be replaced is cheaper than the new substitute or the new control strategy, it is more economical to prevent the resistance.

Since preference is always for the least expensive herbicide that is effective against the major weeds, prevention is generally more economic than adopting a passive attitude with no planning of any preventative programme.

It is predictable that prevention is more economic when the herbicide is repeatedly used or when some herbicides with high risk of causing resistance are applied. In these cases, the situation is aggravated due to the fact that resistance may develop in short periods of time, and the problem may be more serious if the herbicide used is inexpensive.

The economic aspect of resistance should be assessed in the medium term, e.g., in periods of no less than eight years, for evaluating the situation and deciding on how to proceed further.

This aspect of the non-immediate cost of resistance and the fact that resistance usually develops in certain fields, creates difficulties for farmers in understanding the real value of the application of preventative measures.

## 2. IMPORTANT ASPECTS OF RESISTANCE THAT SHOULD BE KNOWN

### 2.1 How to detect and confirm the resistance

The resistance of weeds to the herbicides in cropping areas should be looked at from the agronomical point of view. The resistance concept may present some ambiguities.

Herbicide resistance of a species population occurs when, in normal conditions, the individuals of this species can be controlled by this herbicide at a rate that is selective to the infected crop.

In plants that are not susceptible to a herbicide, it is therefore possible to find populations with different levels of insusceptibility, which cannot be considered resistant populations.

The importance of and value in the correct determination of cases of resistance in order to prevent false positives, have been demonstrated in the guide for determining herbicide resistance (HRAC, 1999; Heap, 2005).

It is necessary to be rigorous in cases when the populations have an incipient or intermediate level of resistance. In such situations, it is sometimes difficult to confirm the presence of resistance.

In order to correctly determine resistance (Heap, 2005), the following conditions should be taken into account:

- the definition of resistance accepted by HRAC should be complied with: this is an inheritable trait (Chueca, 2005);
- the data should be confirmed using scientifically accepted protocols;
- the resistance should be inheritable;
- the practical importance in the field should be demonstrated.

For a weed to be considered resistant, first its population must be abundant, affecting a certain crop, and second, it must be controlled by the herbicide in normal conditions.

When the herbicide is repeatedly used, it is possible to detect *resistant populations*.

There are various methods to detect resistance (Moss, 1995; Beckie, 2000). It is possible to detect it through herbicide trials in the field and through bioassays in greenhouses and laboratory conditions.

In **greenhouses,** the plants of the population suspected to be resistant are treated under controlled conditions. This allows demonstrating resistance more accurately. The assays are conducted with the whole plants, which are generally more reliable, especially with respect to herbicides such as sulphonylureas, phenylureas and carbamates, among others.

There are also **laboratory** assays, which often consist in seeding in Petri dishes in order to later carry out an assessment of the percentage of germination, and/or survival, photosynthetic activity, or other parameters such as measuring enzyme inhibition. Although these methods may have some limitations in the above-mentioned herbicide groups, they are inexpensive and very rapid, often providing interesting results.

A view has been adopted calculating $ED_{50}$, i.e., the rate causing 50 percent effectiveness: a population is resistant if its $ED_{50}$ is ten times higher than the $ED_{50}$ of the population used as the susceptible standard (Heap, 2005).

In all these assays, a standard susceptible population of the weed, as well as one resistant to the herbicide, should be included. These standard populations may come from the same site of the populations yet to be evaluated or from other sites, but it is necessary to fulfil susceptible and resistant requirements, respectively.

In standard susceptible populations, it can usually be guaranteed that they had never been treated with this herbicide.

- *It is very important to detect resistance at its early stage.*
- *The first symptom is that the weed is not controlled by the herbicide as usual.*
- *There are various trials/assays to detect resistance in the field as well in the greenhouse and laboratory.*

Once the susceptible weed population is available, which allows to detect populations that are clearly herbicide-resistant, it becomes easier to detect populations with an incipient or intermediate level of resistance, whose susceptibility lies between two standard populations (Table 2).

## 2.2 Mechanisms of resistance to herbicides and types of resistance

A herbicide causes phytotoxicity to a weed according to a four-step process (Catizone and Satin, 2001). First, the herbicide is intercepted by the weed, retained for a certain time in the outer part of the plant to be later absorbed within it. After moving to the site of action, the period in which the herbicide can be metabolized by the plant to a more active state, it exerts its phytotoxic effect inhibiting the metabolic process of the weed.

There are two types of mechanisms that cause the weed to become resistant. The most obvious one is the alteration of the site of action, the *target site*, which is often described as the key or lock effect, and the other is a change in any of the processes that intervene in the herbicide action, which is known as the metabolic type of resistance, or the *non-target site*.

| ***Biotype*** | ***Resistant to:*** | ***Mechanism of resistance*** | ***References*** |
|---|---|---|---|
| SLR3 | Ariloxyphenoxypropionates<br>Cyclohexanodiones | Resistant<br>ACCasa | Tardif *et al.,* 1993 |
| SLR31 | Ariloxyphenoxypropionates<br>Cyclohexanodiones<br>Sulphonylureas<br>Imidazolinones<br>Dinitroanalines<br>Chloracetamides<br>Isoxazolidinones<br>Carbamates | Resistant to<br>ACCasa<br>Metabolism<br>Membrane<br>Repolarization | Holtum *et al*., 1991<br>Häusler *et al*., 1991<br>Tardif and Powles,<br>1994<br>Christopher *et al*., 1991 |
| VLR69 | Ariloxyphenoxypropionates<br>Cyclohexanodiones<br>Sulphonylureas<br>Imidazolinones<br>Triazines<br>Phenylureas<br>Triazinones<br>Chloracetamides | Resistant to<br>ACCasa<br>Resistant to ALS<br>Metabolism<br>Membrane<br>Repolarization | Burnet *et al*., 1993a<br>Burnet *et al*., 1993b<br>Burnet *et a*l., 1994a<br>Häusler *et al*., 1991<br>Preston, Tardif,<br>Christopher and<br>Powles, unpublished |
| WLR1 | Sulphonylureas<br>Imidazolinones | Resistant to ALS<br>Metabolism | Christopher *et al*., 1992 |
| WLR2 | Triazines<br>Phenylureas<br>Triazinones<br>Amitrol | Metabolism | Burnet *et al*., 1993a<br>Burnet *et al*., 1993b |
| WLR96 | Ariloxyphenoxypropionates<br>Cyclohexanodiones | Resistant to<br>ACCasa<br>Membrane<br>Repolarization | Häusler *et al*., 1991<br>Holtum and Powles,<br>Unpublished |

**Table 2: Examples of standard resistant populations cited in the bibliography**

Source: Powles and Preston, 1995

However, any change hindering the retention, absorption, transport or metabolization of the herbicide may also generate resistant plants. For example, sometimes an increase in cuticle thickness may completely prevent the absorption by the herbicide in the plant, as seen in resistant populations of *Lolium rigidum*, which is resistant to diclofop (De Prado *et al.*, 2001).

There is also a case in which a plant may confine the herbicide in the vacuole, which and prevent it from reaching the target site.

*There are two groups of resistance mechanisms:*

- *through change in the target site;*
- *through changes of some steps of herbicide action (interception, retention, absorption, transport or metabolization: resistance by metabolism.*

The resistance mechanism is described as the process through which the plant is able to nullify the phytotoxic effect of a herbicide (Chueca *et al*., 2005).

A plant resistant to a herbicide can be found in different conditions depending on its mechanism of resistance. Thus, **crossed resistance** is when the plant biotype has developed a single mechanism of resistance to a herbicide, which also enables it to resist other herbicides with the same mode of action (Chueca *et al*., 2005).

A biotype with **multiple resistance** is one that has developed one or more mechanisms of resistance to various herbicides with different modes of action.

## 2.3 Selection pressure

The presence of resistant plants in a population is, *per se*, extraneous to the herbicide itself. It only selects biotypes of the population with the trait that renders it non-susceptible to the herbicide. Thus, the **selection pressure** of a herbicide, which is the effect of herbicide treatment on weeds in the field, is also able to select resistant biotypes.

It is very important to take into account that the intensity of selection pressure depends on the type of treatment and/or herbicide, its formulation, frequency of application and the biological characteristics of the weed and the crop.

Herbicide selection pressure should be seen in the group of actions carried out in the field: tillage, crop rotation, use of other control methods and cropping. Thus, a herbicide with low selection pressure, used sporadically and alternating with other non-chemical control methods, will have a low risk of causing problems of resistance.

Some herbicide groups have a higher a selection pressure than others. The effect of the herbicide selection pressure according to Storrie (2005) is shown in Table 3[2].

| *Herbicide groups (HRAC)* | *Years of application* | *Risk of causing resistance* |
|---|---|---|
| *A* | *6-8* | *High* |
| *B* | *4* | *High* |
| *C* | *10-15* | *Medium* |
| *D* | *10-15* | *Medium* |
| *F* | *10* | *Medium* |
| *I* | *Unknown* | *Low* |
| *L* | *>15* | *Low* |
| *M* | *15* | *Low* |

**Table 3: No. of required years of herbicide application for weeds to develop resistance**

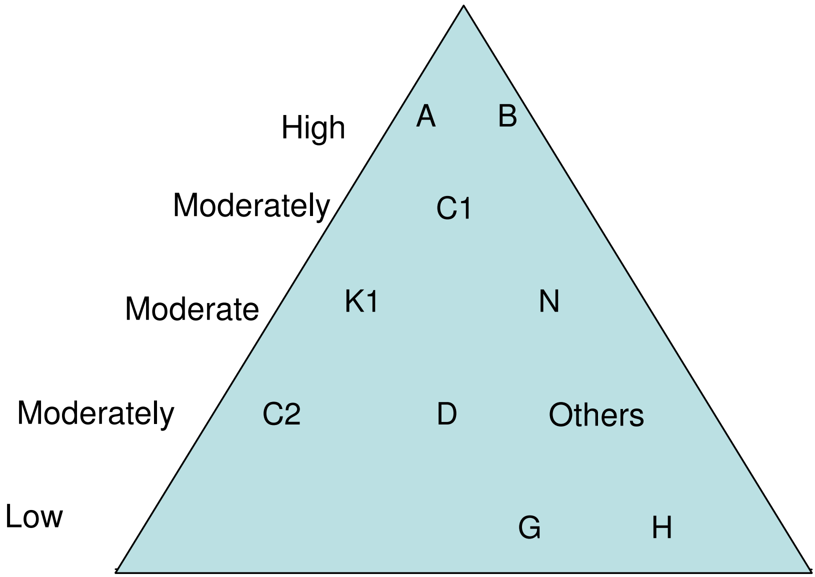
Source: Preston *et al.,* 1999, cited in Storrie, 2006

Herbicides that result in resistance after a few years of use are those with a high selection pressure.

[2] See the entire herbicide classification table in Chapter 3.1.

Beckie (2006) has another viewpoint, shown illustratively in a triangle, in which selection pressure of different herbicide groups is classified according to its mode of action (Figure 4).

**Figure 4: Descriptive triangle of selection pressure exerted by different herbicide groups classified according to HRAC Criteria.**




Source: Beckie, 2006

Since selection pressure is an attribute of each herbicide, it is now recommended to use the herbicides in a determined sequence. Moss (2006) thus describes and justifies a determined herbicide sequence to control *Alopecurus myosuroides*.

## 2.4 Fitness

Each aspect of species biology contributes to its *fitness,* i.e., germination or regrowth capacity and speed, development vigour, fertility, etc. In each aspect, a biotype may acquire or lose the advantage of surviving competition with other biotypes of the same species.

The expression of the resistance trait to the herbicide assumes a fitness higher or lower than 1. When higher than 1, the resistant plants have a greater advantage in surviving over the susceptible ones. On the other hand, when it is lower than 1, the resistant plants do not have any advantage over the susceptible population.

When the *fitness* value is lower than 1, once the resistance is detected, if the herbicide that causes the resistance is no longer applied, in time the population will consist of susceptible plants.

## 2.5 Flora inversion

Finally, another concept to be taken into consideration is flora inversion. This phenomenon consists of the change of flora in the field treated continuously with the same type of weed control system (Chueca *et al.,* 2005).

An example of this phenomenon is the increased stand of grassweeds that occurs in winter cereals when there is improper use of phenoxyacetic herbicides that only control broadleaf weeds. Another example is the increase of Sorghum halepense in maize fields, where the herbicides used are only those that are effective against annual species and that do not exert any effect over this perennial grass.

It is important to understand this concept in order not to confuse resistance with flora inversion. In addition, as seen below in the chapter on Integrated Control, it is useful to understand the special case of flora inversion when resistant plants foreign to the farm are allowed to invade the fields, becoming a source of resistance there.

# 3. PREVENTION AND MANAGEMENT OF RESISTANCE

## 3.1 Chemical weed control for resistance management

Since weed resistance to herbicides is a consequence of a inappropriate herbicide use, it is essential to have better knowledge of these chemicals to use them better and to adopt a positive and pro-active attitude in case of herbicide resistance.

In fact, several decisions should be taken in **resistance prevention and management,** which should be based on the correct knowledge of the mechanisms and mode of action of resistance of each active ingredient.

The following section will therefore review the available herbicides, their main mechanisms of action and those that cause the major problems of weed resistance.

Special mention will be given to the herbicide glyphosate, because of the significance that its resistance has acquired and since it is the herbicide most widely used globally; with the planting of genetically modified resistant crops, its use has intensified.

### *3.1.1 Available herbicides and HRAC classification*

There are many available herbicides in the market, classified according their mode of action in 24 groups (Mallory-Smith, 2003), also known as the HRAC working group classification (Table 4). As shown in Table 4, in the Spanish market, there are more than 100 active ingredients, which are part of more than 600 commercial formulations.

Herbicide activity to control weeds is based on several essential metabolic processes.

*There is a high number of active ingredients for weed control, but:*

- *the options are limited for each weed in a particular crop;*
- *new herbicides are developed with difficulty and do not always have new mechanisms of action.*

Although there are a large number of herbicide active ingredients and a relatively large number of mechanisms of action, there are few options for controlling certain species in a particular crop.

- *Herbicides are classified in groups according to their mechanism of action;*
- *a different letter (HRAC) or number (WSSA) is assigned to every group.*

Thus, for the control of *Lolium rigidum* or *Alopecurus myosuroides* in winter cereals in Spain (2006), there are only eight active ingredients belonging to four different groups. For the control of *Sorghum halepense* in maize, there are three herbicides belonging to the same group. For control of *Phalaris,* there are eight active ingredients belonging to four different HRAC groups.

This aspect is of vital importance for managing resistance, i.e., the capacity for changing or alternating the active ingredients is very limited. For this reason, any change in crop management would be useful to delay the emergence of resistance. For example, alternating with an active ingredient, even belonging to the same group, implies a small change. Replacing a post-emergence treatment by a pre-emergence one is not an ideal option, but it may be useful in this case.

Due to this scarcity of alternatives of herbicides and given that the development of new active ingredients belonging to a different group is very difficult, herbicide use must be combined with other control strategies.

The herbicide groups having a high selection pressure present a high risk of causing weed resistance in particular crops.

Herbicides that favour increased risk of resistance:

- act only in one target site;
- have common increased effectiveness;
- show persistence in weed control;
- are easily metabolized by weeds;
- are applied in large areas and repeatedly in a crop cycle continuously over the years;
- do not follow the conditions indicated in the product label, i.e., are applied at a rate higher or lower than the recommended rate, or are applied too early or too late.

*Herbicides should be used according to the label instructions:*

- *at the appropriate state of weed development;*
- *at the appropriate crop stage;*
- *with the correct rate;*
- *under proper climate and soil conditions.*

*Remember:*

- *use the lowest effective rate to reach the maximum efficacy.*

| HRAC GROUP | MODE OF ACTION | CHEMICAL GROUP | ACTIVE INGREDIENT |
|---|---|---|---|
| A | Acetil CoA carboxyl·lase (ACCasa) Inhibitors | Ariloxyphenoxypropionates (FOPs)<br><br><br><br>Cyclohexanodiones (DIMs) | clodinafop, diclofop-methyl<br>fenoxaprop-p-ethyl, fluazifop-p-butyl<br>haloxifop-r-methyl, propaquizafop<br>quizalofop-p-ethyl<br>clethodim, cycloxidim, tralkoxidim, profoxidim, tepraloxidim |
| B | Acetolactate sintetase ALS Inhibitors | Sulfonylureas<br><br><br><br><br><br>Imidazolinones<br>Pirimidiniltiobenzoates<br>Triazolpirimidines | amidosulfuron, azimsulfuron<br>bensulfuron-methyl, cinosulfuron, chlorsulforon,<br>flazasulfuron, flupirsulfuron, imazosulfuron,<br>iodosulfuron mesosulfuron, metsulfuron, nicosulfuron,<br>prosulfuron rimsulfuron,<br>sulfosulfuron, tifensulfuron, triasulfuron, tribenuron-methyl<br>imazametabenz, imazamox<br>bispiribac-na<br>florasulam |
| C1 | Inhibitors of photosynthesis in photosystem II | Triazines<br><br>Triazinones<br>Uracils<br>Piridazinones<br>Fenil-carbamates | atrazine, simazine, terbutilazine<br><br>metribuzin<br>lenacil, terbacil<br>chloridazon<br>desmedifam, phenmedifam |
| C2 | Inhibitors of photosynthesis in photosystem II | Ureas<br><br>Amides | chlortoluron, diuron, fluometuron, isoproturon,<br>linuron, metobromuron,<br>propanil |
| C3 | Inhibitors of photosynthesis in photosystem II | Nitrils<br><br>Benzothiadiazinone | bromoxinil, ioxynil<br><br>bentazon |

| HRAC GROUP | MODE OF ACTION | CHEMICAL GROUP | ACTIVE INGREDIENT |
|---|---|---|---|
| D | Acceptor of electrons in photosystem I | Bipiridilis | diquat, paraquat |
| E | Inhibition of protopofrinogen oxidase (PPO) | Difenilethers<br>Fenilpirazols<br>Oxadiazols | bifenox, oxifluorfen<br>piraflufen-ethyl<br>oxadiazon |
| F1 | Bleachers: inhibitors of carotene biosynthesis (PDS) | Piridazinones<br>Piridincarboxamides<br>Others | ----<br>diflufenican<br>benflubutamide, flurochloridone |
| F2 | Bleachers: inhibitors of 4-HPPD | Triketones<br>Isoxazoles | sulcotrione, mesotrione<br>isoxaflutol |
| F3 | Bleaching: inhibitors carotene | Difenileters<br>Isoxazolidinones<br>Triazols | aclonifen<br>clomazone<br>amitrol (=aminotriazol) |
| G | Inhibitors EPSP asa | Glycines | glyphosate |
| H | Inhibitors glutamine synthetase | Phosphinic acids | glufosinate |
| I | Inhibitors DHP synthetase | Carbamates | asulam |
| K1 | Inhibitors of Microtubule assembly inhibition | Benzoic Acid<br>Benzamides<br>Dinitroanilines | chlortal<br>propizamide<br>benfluralin, etalfluralin, oryzalin, pendimethalin, trifluralin |
| K2 | Mitosis inhibitors | Carbamatos | chlorprofam |
| K3 | Inhibitors of cell division | Acetamides<br>Benzamides<br>Chloroacetamides | napropamide<br>propizamide<br>acetochlor, alachlor, dimetanamide, s-metolachlor, propachlor |
| L | Inhibitors of cell wall synthesis | Benzamides | isoxaben |

| HRAC GROUP | MODE OF ACTION | CHEMICAL GROUP | ACTIVE INGREDIENT |
|---|---|---|---|
| | | Nitrils | dichlobenil |
| M | Membrane dysfunction | ---- | ---- |
| N | Inhibitors lipid synthesis. They do not inhibit ACCase | Thiocarbamates<br>Benzofurans | molinate, prosulfocarb, tiobencarb, tiocarbazil, trillate<br>benfuresate, etofumesate |
| | | | |
| O | Similar action to indolacetic acid auxin synthesis | Fenoxicarboxylic acids<br><br>Benzoic acids<br><br>Carboxylic acids<br><br>Quinolinacarboxylic acids | 2,4-D, 2,4 DP, MCPA, MCPP<br><br>dicamba<br><br>chlopyralid, fluroxypir, picloram, triclopyr<br><br>quinclorac |
| P | Inhibitors of auxyn transport | Phtalamates | naptalam |
| R | ---- | ---- | ---- |
| S | ---- | ---- | ---- |
| Z | Unknown | Pirazolin | difenzoquat |
| | | Organic arsenicals | ---- |

**Table 4: Available herbicides in the Spanish market in 2006, grouped according to their mode of action and HRAC classification**

### *3.1.2 Mixtures, rotations and herbicide sequences*

An aspect deserving attention is the use of herbicide mixtures (Arvalis, 2006; Beckie, 2006; Moss, 2005). It is also important to differentiate herbicide sequences and rotations of mixtures.

**Sequence of herbicide treatment** is understood as the application of two or more different herbicides or of the same herbicide applied in split rates in the same crop but with a lapse of time in between, normally one or two weeks. In this case, when the period of the time between applications is too short, for instance a few hours, the effect of the sequence can be equal to a mixture.

**Rotation,** however, is understood as the application of various herbicides but in different stages of the crop.

When two or more active ingredients are **mixed**, the first principle to follow is to increase efficacy. The increase would achieve higher weed control or a greater effect over a single species that is difficult to control with the application of a single herbicide.

However, herbicide mixtures cause other consequences – some of them still not well known – which are related to their mechanism of action by which they are metabolized by the plant, and through interactions between these processes. Obviously, in order to be mixed, the herbicides should be physically and chemically compatible (i.e., they should not flocculate or react adversely).

When herbicides are mixed with different mechanism of action, a selection of biotypes resistant to both active substances may occur.

The mode in which the herbicides metabolize is also affected when they are mixed. If they are metabolized in the same way, the selection pressure of the mixture continues to be high.

Finally, it is important to consider the possible interaction between the active ingredients. In this way, a simple additive action may be produced or a synergy, which means that the effectiveness obtained is higher than the sum of the effect of both herbicides. There is a third possibility, i.e., antagonism among them, in which the effectiveness obtained will be less than expected.

For all of these reasons, the rates of herbicides in mixtures are variable. Sometimes, the rates should be the same as that when the substances are used separately; in the case of synergy, the rate should be lower, and in the case of antagonism, it should be higher to obtain the same effects or to use these products in a sequence to avoid having to use a higher rate.

According to Beckie (2006), the following should be taken into account at the time of preparing a mixture.

Mixed herbicides should have similar effectiveness over the target weeds:

- their persistence should be of the same magnitude;
- the degradation mechanisms by the weeds should also be different;
- the rates should be adjusted to the current interactions between the mixed herbicides.

When the rotation and the herbicide mixtures are applied accurately, it is possible to delay resistance (Powles *et al.*, 1997). In any case, the efficacy of the application should be high to ensure that the seed bank in the soil will not be enhanced with seeds from resistant biotypes.

A controversial aspect is whether or not to continue using a herbicide with problems of resistance in a mixture. One view is to consider that this product is useless and dead and that its use should be stopped. Another opposing view is that the herbicide should not be abandoned since it continues controlling other species and may solve the problem when mixed with another herbicide that is effective over the resistant species.

However, if the second view prevails, then it may enable the herbicide resistance to be generated in other weed species.

### *3.1.3 Weed resistance to glyphosate*

As previously indicated, glyphosate is a herbicide that deserves special attention.

In a recent review, Powles and Preston (2006) describe the present situation of resistance to glyphosate. The worldwide consumption of this herbicide is high since it is used in several crops and is applied in pre-planting and post-emergence directly on the weeds. Its use in soil conservation systems and, more recently, in genetically modified crops resistant to its application, have also increased its use. Its application in non-agricultural and forest areas is also important.

Due to this widespread use, many new biotypes have evolved resistance to glyphosate. According to Heap (2006), there are 12 weed species resistant to glyphosate. This is surprising since the resistance emerged after a long period of glyphosate use, over 20 years, and in high quantities of the herbicide. In the past, it was considered not likely to develop any resistance to glyphosate (Bradshaw *et al*., 1997).

At present, not only is there resistance of one species to glyphosate, but also both the number of resistant species and the number of sites of the world increase. The most recent was *Sorghum halepense* in Argentina, which has become of special importance, since here the problem is with a perennial plant prevailing in summer crops, such as maize and soybean (Leguizamon, 2006).

There are several publications related to glyphosate resistance; in Australia, for example, various initiatives of the National Glyphosate Sustainability Working Group (2006) are well known. It is also interesting to consult the websites of Monsanto (2006) and Syngenta (2006), where this topic is widely explained with abundant references.

The mechanisms of the weeds to avoid glyphosate action are gene mutation expressed by aminoacid 106 of the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) as metabolic resistance, in which the herbicide transport is reduced in the plant meristems. Heap (2006) refers to a *Lolium* *rigidum* population having multiple resistance to glyphosate with three different mechanisms of action.

### *3.1.4 The use of genetically modified crops resistant to glyphosate and weed control*

There is a dual perspective on the use of genetically modified crops resistant to herbicides as concerns weed control.

The use of these crops sporadically, reasonably, and not continuously but systematically may bring another possibility for herbicide rotations, and may also be a good tool for improved weed management. This possibility helps to prevent problems of herbicide resistance.

However, when used continuously, the risk related to herbicide use – flora inversion, residues in water and resistance – increased substantially.

All this is highly relevant in the use of glyphosate. Its broad spectrum of action and high efficacy may promote flora inversion, particularly when it is used continuously for several years in large areas. In addition, since it is a low-cost herbicide, its use can become massive.

Further, its use is particularly dangerous when weeds of the same genus of the crop prevail. This phenomenon may cause crossing so that the weed will inherit the resistance conferred to the crop. Examples are wild rice in rice crops and various cruciferous plants in rape. Where this is not the situation, the risk comes from the repetitive herbicide use.

A positive aspect of glyphosate use in genetically modified crops is that it makes it possible to easily solve some cases of weed infestations, such as late annual grassweeds infestations in maize and soybean, in which other herbicides cannot be used, which are normally less effective and more expensive.

The recommendations of CASAFE-CIAFA (2006) for the prevention and management of *Sorghum halepense* resistance in soybean are:

- plant HR soybean in a plot free of emerged weeds, using a recommended herbicide and, if resistant plant biotypes are observed, proceed to their mechanical removal in order to avoid seed setting and dispersal;
- plant certified seeds, free of weed seeds. The use of seeds from infested plots may spread the weed to other areas;
- during the harvesting process, start the work in plots that are not weed-infested and leave the others to the end;
- once the harvest is complete, carry out an exhaustive cleaning of the machinery used in the plots; all materials collected from this operation should be burned;
- keep a continued watch over the plots before and after each herbicide application for early detection of any possible failure;
- avoid the flowering and seed setting of *Sorghum halepense* plants – one of the main objectives. In case the plants are able to seed set, it will be necessary to safely cut and destroy the weed panicles to prevent the spreading of weed seed.

*Herbicide-resistant genetically modified crops are a double-edged tool for weed control:*

- *on the one hand, they enable farmers to implement improved herbicide rotation;*
- *on the other hand, they may bring about the excessive use of the herbicide.*

*It is for this reason that they should be used with caution, following the label instructions.*

## References on chemical weed control and resistance


**ARVALIS.** 2006. *Melanges de produits phytosanitaires*. (available at http://www.arvalisinstitutduvegetal.fr/fr/melanges.asp). Consulted on 28 December 2006.

**Beckie, H.J.L., Heap, I.M., Smeda, R.J and Hall L.M.** 2000. Screening for herbicide resistance in weeds. *Weed Technology*, 14:428-415 pp.

**Beckie, H.J.** 2006. Herbicide-resistant weeds: management tactics and practices. *Weed Technology*, 20:793-814 pp.

**Bernal E., Charles, R., Riches, J. & Caseley, C**. 2000. P*revención y manejo de malezas resistentes a herbicidas en arroz: experiencias en América Central con Echinochloa colona* Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba (Costa Rica), 136 pp.

**Bradshaw, L.D., Padgette S.R., Kimball, S.L. & Wells, B.H**. 1997. Perspectivas on glyphosate resistance. *Weed Technol*ogy, 11:189-198.

**CASAFE-CIAFA**. 2006. Se confirma la resistencia de un biotipo de *Sorghum halepense* a glifosato en Tartagal, Salta. Información de prensa, 16 de agosto. http://www.monsanto.com.ar/h/biblioteca/informes/AlepoResistComunicado2006.pdf

**Catizone, P. & Zanin, G.** 2001. *Malerbologia*. Bologna, Italy, Patron Editore. 925 pp.

**Chueca, C., Cirujeda, A., De Prado, R., Diaz, E., Ortas, L., Taberner, A. & Zaragoza, C**. 2005. Colección de folletos sobre manejo de poblaciones resistentes en *Papaver, Lolium, Avena y Echinochloa*. SEMh Grupo de Trabajo CPRH.

**Colquhoun, J.** 2001. *Perennial weed biology and management*. Oregon, USA, Oregon State University.

**CRC for Australian Weed Management.** 2006. *Integrated weed management manual.* (available at http://www.weeds.crc.org.au). Consulted on 27 December 2006.

**CRC for Australian Weed Management** 2005. *Presentation of information sessions to small groups en Introductory weed management manual.* 15 pp.

**De Prado, R. & Franco, A.** 2004. Cross-resistance and herbicide metabolism in grass weeds in Europe: biochemical and physiological aspects. *Weed Science*, 52:441-447 pp.

**EEAOC** (Estación Experimental Agroindustrial Obispo Colombres). 2006. Av. William Cross 3150 - C.P. T4101XAC- Las Talitas – Tucumán, Argentina. (available at http://www.eeaoc.org.ar). Consulted on 28 December 2006.

**EPPO** (European and Mediterranean Plant Protection Organization). 2002. *Efficacy evaluation of plant protection products.* Resistance risk analysis 1/213(2) pp.

**FAO** 1996. *Manejo de malezas para países en desarrollo*. FAO Producción y Protección Vegetal. Edit. Labrada R., Parker C. y Caseley J., Rome, 404 pp. (Available at: http://www.fao.org/docrep/t1147s/t1147s00.htm)

**FAO** 1997. Reunión regional resistencia de malezas a herbicidas. Jaboticabal, Unesp, Brasil. (available at: http://www.fao.org/ag/AGP/AGPP/IPM/Weeds/Download/ihrcla.pdf)

**FAO** 2001. Summary of the Workshop on *Echinochloa* Control. Institute of Plant Protection, Beijing, China.

**Farmassist** 2006. *Información de Syngenta sobre manejo de resistencias* (available at http://www.farmassist.com/sitemap.asp). Consulted on 28 December 2006.

**Fernández-Quintanilla, C., Garrido, M. & Zaragoza, C.,** eds. 1999. *Control integrado de las malezas. Buenas Prácticas Agrícolas*. Phytoma España S.L. Valencia, Spain. 271 pp.

**Heap, I.** 2005. *Criteria for confirmation of herbicide-resistant weeds – with specific emphasis on confirming low level resistance* (available at http://www.weedscience.com).

**Heap, I.** 2006. *The international survey of herbicide-resistant weeds*. 10 December 2006. (available at http://www.weedscience.com).

**Hobbs, P.R. & Bellinder, R.R.** 2004. Weed management in less developed countries. *In* M. Dekker, ed. *Encyclopedia of Plant and Crop Science*. Marcel Dekker, Inc. NY, NY 1295-1298 pp.

**HRAC.** 1999. *Detecting herbicide resistance. Guidelines for conducting diagnostic tests and interpreting results* (available at http://www.plantprotection.org/hrac/detecting.html).

**Labrada, R.** 1996. FAO. Weed control in rice. *In* "*Weed management in rice*" edited by Auld B. A. & Kim K.U., FAO Plant Production and Protection Paper N°139. Rome, 3-5 pp.

**Leguizamón, E.** 2006. *Sorghum halepense*. L. Pers. (Sorgo de Alepo): base de conocimientos para su manejo en sistemas de producción. Unpublished.

**Luchin, M., Zanin, G. & Parrini, P.** 2001. Resistenza delle malerbe agli erbicidi. *In* P. Catizone & G. Zanin. 2001. *Malerbologia*. Bologna, Italy, Patron Editore.

**Malik, R.K. & Brown, H., Cussans, G.W. Devine, M.D. Duke, S.O., Fernández Quintanilla, C., Helweg, A., Labrada, R.E., Landes, M., Kudsk, P. eds. & Streibig, J.C.** 1996. *Herbicide resistant weed problems in developing world and methods to overcome them. Proceedings of the Second International Weed Control Congress,* Copenhagen, Denmark, 25-28 June 1996.

**Mallory-Smith, C.A. & Retzingher, E.J.** 2003. Revised classification of herbicides by site of action for weed resistance management strategies. *Weed Technology,* 17:605-619 pp.

**Marsh S., Casimero, M., Llewellyn, R. & Beltran, J.** 2006. Working with farmers to develop practical weed management techniques for direct-seeded rice in the Philippines. *In* Proceedings of APEN International Conference, 6-8 March 2006, Beechworth, Victoria, Australia.

**Monsanto Argentina, Departamento Técnico.** 2006. Investigación sobre la dificultad de controlar *Sorghum halepense* en la Argentina. *Boletín Técnico*. (available at: http://www.planetasoja.com/trabajos/trabajos800.php?id1=6279&idSec=21&publi= – in Spanish). Consulted on 21 December 2006.

**Monsanto Company.** 2006. *Información sobre resistencias*. (available www.weedresistancemanagement.com). Consulted on 28 December 2006.

**Moss, S.R.** 2006. Herbicide resistance: new threats, new solutions? HGCA Conference, 25 and 26 January 2006. *Arable crop protection in the balance: profit and the environment*, available at: http://www.hgca.com/publications/documents/cropresearch/Paper_12_Stephen_Moss.pdf

**Moss, S.R., Clarke, J.H. & Tatnell, L.V.** 2005. Herbicide Resistance Management Evaluation of Strategies (HeRMES). Research Project PT0225 Final Report. (available at http://www.defra.gov.uk/science/project_data/DocumentLibrary/PT0225/PT0225_2663_FRP.doc)

**Moss, S.R.** 1995. *Techniques* for determining herbicide resistance. Proceedings of the Brighton Crop Protection Conference –-Weeds, 547-556 pp.

**Mueller, T. C., Mitchell, P.D., Young, B.G. & Culpepper, A.S.** 2005. Proactive versus reactive management of glyphosate-resistant or tolerant weeds. *Weed Technology*, 19:924-933 pp.

**National Glyphosate Sustainability Working Group**. 2006. *Keeping glyphosate resistance rare in Australian cropping*. Brochure. 2 pp.

**Neve, P. & Powles, S.** 2005 High survival frequencies at low herbicide use rates in populations of Lolium rigidum result in rapid evolution of herbicide resistance. *Heredity*, 95: 485–492 pp.

**Orson, J.H.** 1999. The cost to the farmer of herbicide resistance. *Weed Technology*, 13:607-611 pp.

**Owe, M.D.K.** 1997. Risks and benefits of weed management technologies. In R. De Prado., J. Jorrin & L. García-Torres, eds. *Weed and crop resistance to herbicides*. Klouwer Academic Press Publishers. London, 291-297 pp.

**Pesticides Safety Directorate.** 2005. Resistance Action Group: September 2005 Special Meeting. (Avaliable at: http://www.pesticides.gov.uk/rags.asp?id=714#September2005)

**Pesticide Safety Directorate.** 2006. Resistance Action Group: www.pesticides.gov.uk/rags.asp

**Powles, S.B. & Preston, C.** 2006. Evolved glyphosate resistance in plants: biochemical and genetic basis of resistance. *Weed Technology*, 20:282–289 pp.

**Powles, S.B., Preston, C., Bryan I. & Jutsum, A.** 1997. Herbicide resistance: impact and management. *Adv. Agron*., 58:57-93 pp.

**Powles S. & Preston, C.** 1995. *Herbicide cross resistance and multiple resistance in plants*. http://www.pestresistance.com/Publications/HerbicideCrossResistanceandMultipleResistance/tabid/224/Default.aspx

**Prado, R., De, Prado, J.L. Osuna, M.D., Taberner, A. & Heredia, A.** 2001. Is Diclofop-methyl resistance in *Lolium rigidum* associated with a lack of penetration. The BCPC Conference: Weeds, 2001, Volume 1 and Volume 2. Proceedings of an international conference, Brighton, UK, 12-15 November 2001, 2001 8 A: 545-550 pp.

**Preston, C., Stewart, V., Storrie, A. & Walter, S.** 2006. Integrated weed management in Australian cropping systems CRC for Australian Weed Management, 248 pp.

**Qin Yu, Cairns, A. & Powles, S.** 2007. *Glyphosate, paraquat and ACCase multiple herbicide resistance evolved in a Lolium rigidum biotype*. Planta 225 (2): 499-513 pp.

**Rakesh, C.** 2004a. *Managing herbicide-resistant weeds.* West Virginia, USA, Cooperative Extension Service, West Virginia University.

**Rakesh, C.** 2004b. *Update on ALS-resistant Johnsongrass in Hardy County*. West Virginia, USA, Cooperative Extension Service, West Virginia University.

**Sans, X. & Fernández-Quintanilla,** eds. 1997. *Biología de las malezas de España*. Valencia, Spain, Phytoma España S.L.. 117 pp.

**Storrie, A.** 2006. *Herbicide resistance mechanisms and common HR misconceptions. 2006 grains research update for irrigation croppers*. Brochure. 3 pp.

**Urbano, J.M., Borrego, A., Torres, V., Jiménez, C., León, J.M. & Barnes, J.** 2005. Glyphosate-resistant hairy fleabane (*Conyza bonariensis*) in Spain. Weed Science Society of America. Abstract. 118 pp.

**Valverde, B.** 2001. Weed management in Latin America. *Pesticide Outlook* 13: 79-81 pp.

**Valverde, B.** 2004. Manejo de la resistencia a los herbicidas en los países en desarrollo. In *Manejo de malezas para países en desarrollo*, by R.E. Labrada. Addendum. FAO. Rome (Available at: http://www.fao.org/docrep/007/y5031s/y5031s0h.htm#bm17)

**WAHRI.** Web site: http://wahri.uwa.edu.au/.

## 3.2 Non-chemical systems for preventing herbicide resistance

### *3.1.1 Introduction*

Generally, the available information on the prevention of resistance for technical personnel and farmers puts more emphasis on the alternation of herbicides with different mode of action. Other weed control systems are rarely described as alternatives despite their recognized usefulness in reducing selection pressure, with the assumption that their features are sufficiently understood. These non-chemical methods are considered old-fashioned and difficult to mechanize, but are currently gaining great importance for the prevention and control of herbicide-resistant weeds.

In this chapter, some preventative and agronomic methods are described, such as rotations, intercropping and delayed planning, among others. Some advantages and disadvantages of physical methods, including hand weeding, slashing, conventional tillage, precision weeding and thermic weeding, are discussed. Special attention is given to mulching with plastic, biodegradable materials and paper, as well as the use of plant residues for covering soil, their direct effects (barrier and allelopathy) and indirect effects on the environment.

### *3.1.2 Preventative methods*

Prevention methods aim to prevent the spread of seeds and propagules, i.e., the establishment of troublesome species. They are very effective if implemented in the long term, but unfortunately are not widely used due to their apparently low efficacy. Generally, these measures are effective in reducing the weed seed bank in the soil, preventing the invasion of new indigenous or exotic species (use of certified clean seed, substrates, substrates and clean organic amendments [compost], hindering the spread of weeds (improving drainage, weeding in patches, post-harvest cleaning), and above all, through early detection of infestations (Zaragoza, 1999). For prevention, some principles should be taken into account as a general strategy (Table 5) as well as risk factors for evolving resistance (Table 6).

|  |
|---|
| 1. Assess the resistance risk factors of resistance in each field, plot or land. The precise weed identification is essential.<br>2. Regularly monitor the fields and take early action to prevent patches and spreading (scouting, written records, hand weeding).<br>3. Minimize seed spread within and between fields (cleaning machinery, equipments, irrigation water, manure, grazing, etc.).<br>4. Integrate chemical and non-chemical methods in a long-term strategy (tillage, rotation, planting date, varieties and irrigation management). |

**Table 5: Principles of the overall strategy for preventing herbicide resistance**

Source: WRAG, 2003

| ***Factors*** | ***Low Risk*** | ***High Risk*** |
|---|---|---|
| Crop alternatives | Complete rotation | Monocropping |
| Level of weed infestation | Low | High |
| Tillage system | Annual till | Continuous no till |
| Type of weeding | Only mechanical | Only with herbicides |
| Types of applied herbicides in rotation | With different modes of action | With only one mode of action |
| Herbicide effectiveness during the last three years | Good | It has declined slowly during the last years. |
| Resistance developed in the area | No | Yes |

**Table 6: Risks factors in developing resistance according to agronomical practices**

Source: CPRH, 2000 and WRAG, 2003

### *3.1.3 Agronomical methods*

Agronomical or cultural methods mainly include crop rotation and intercropping. Crop rotations are valuable in controlling weeds and other pests and diseases. They require cropped plants to proliferate, but weeds –

although apparently they are not so specific – tend to be closely associated with the crops (e.g., *Lolium* and *Avena* in winter cereals; *Solanum nigrum* in tomato; *Abutilon* in maize and cotton; *Echinochloa, Hetheranthera, Scirpus* in rice). However, when a species that is well adapted to monocropping is controlled, once the rotation is implemented, other weeds will appear, occupying its space, which normally are not resistant.

It has often been observed that high crop yields are obtained with the leguminous forage–cereal rotation, despite the higher weed abundance in the leguminous than in cereal monocropping (Craig Stevenson *et al*., 1998). The interest of these alternatives is based on the possibility of changing the control tactic (planting date, tillage, herbicides, and others), which is valuable in preventing resistances (Table 7).

Types of **crop rotations** are:

- rotation of dates: planting the crops in different periods. In this way it is possible to break life cycles of several weeds. For example, it is possible to control early emergence of a species when planting the crop later than usual, or the opposite, planting the crop early in a way that weeds will emerge when the crop has already some competitive advantages;
- cycle rotation: alternating annual crops with biennials and/or perennials (e.g., wheat, maize, cotton vs alfalfa or pastures);
- rotation of occupied space: alternating two or more crops in rows to enable the weed control in the interrow with crops occupying the space available;
- rotation at the time of harvesting: grazing or slashing a crop for grains with the aim to disturb the life cycle of weeds and prevent their spread.

Some examples are:

- millet-peanut-fallow;
- maize-cereal-alfalfa;
- pepper-onion-cereal;
- spinach-beans-tomato;

- radish-lettuce-cabbage;
- cabbage-cereal.

| Pastures | Crops |
|---|---|
| • Use a high sowing rate<br>• Prepare hay or silo to reduce weed seed production<br>• Ensure a good pasture competition<br>• Graze<br>• Cultivate fallow. | • Ensure that crops are dense and competitive<br>• Till if possible<br>• Use crops for green cover<br>• Delay planting<br>• Use crops for forage<br>• Remove weed seeds at harvest<br>• Burn the stubbles if possible. |

**Table 7: Prevention of herbicide resistance through non-chemical procedures**

Source: GAP, 2005

The disadvantages of rotations generally relate to farmers' lack of possibilities to replace one crop by another due to problems of economical feasibility in the short term. It should be pointed out that there are a very few economically feasible alternatives to cereals in arid areas. It is also difficult to find alternatives for rice in saline or compacted soils with poor structure. In addition, although living covers can be planted in the interrows, woody plants cannot be replaced in the short or medium term.

**Intercropped plants** can be useful when herbicides are not wanted. Some of these crop associations are well adapted to take advantage of the available resources. A known example is the maize-beans-pumpkin association, which is typical to American indigenous agriculture still very much practised in European humid zones. Maize allows beans to climb towards the light and taking advantage of nitrogen fixed by the leguminous, while pumpkin spreads on soil, benefiting from shade and available moisture, and in turn provides shade to the weeds. Other favourable vegetable associations have been known for centuries, such as lettuce-carrot, pepper-onion, zucchini-green beans. Other examples are those that take advantage of vertical space, such as cacaobanana-coffee. Another possibility in woody plants is to take advantage of the interrows, by planting with vegetable crops before the trees reach productive stages (artichoke in olives, tomato in hazel, etc.).

Due to low productivity of traditionally associated crops, intercropping in rows is currently suggested to improve the competitive capacity of some vegetables with very limited foliage. In this way, better results have been achieved in light interception, shorter critical periods for weeding and higher yields in leek crops intercropped with celery than when leek is cropped alone (Baumann and Kropff, 1999).

Some intercropped plants, “covers” or “living covers”, are very much used in woody plants (e.g., barley or some brassicae in olives, leguminous crops in orchards). The main disadvantage of these covers in orchards is the need to limit their competition, especially in dry areas, in order to prevent reduced production. It has been observed that vigour reduction of a vineyard grown in dry arid areas can be significant (Zaragoza Larios and Delgado, 1996). The use of covers successively to leave dry mulch until the next crop is of great interest since it theoretically enables a better and integrated soil use, protection from erosion, preservation of moisture as well as the prevention of weed invasion, other insect pests, some diseases and nitrate leaching. Their combined use with slashing may help to reduce herbicide selection pressure.

Other cultural methods are **varietal selection** and **planting distance** or planting density. The growth speed and the foliage expansion are characteristics defining the competitiveness of a plant. The better adapted varieties that grow more quickly in their initial stages will compete better with weeds. It is well known that barley is more competitive than wheat with respect to annual grassweeds. In experiments carried out in the dry arid area of Alcalá de Henares, Spain, winter wheat and barley varieties, with greater height and higher tillering are more competitive against *Lolium rigidum* or *Avena sterilis* (Torner *et al.*, 1999). Equally recommendable are the techniques that favour maximum initial crop growth. The increase of planting density may be used for reducing weed competition or to compensate some plant mortality due to some non-selective weeding practices. Another example is irrigated maize: its great ability to compete in the Ebro Valley is well known. With the aim of its better use, the emerging crop is often left non-irrigated, forcing it to develop its maximum root system and delay weed germination. When it is finally irrigated, weeds emerge when the crop is able to grow fast and able to smoother them.

| |
|---|
| *Manage and prevent the resistance in the following way:*<br>• *Monitoring the field regularly*<br>• *Integrating chemical and agronomical methods*<br>• *Rotating crops with different cycles*<br>• *Selecting more competitive varieties*<br>• *Delaying the date of planting*<br>• *Grazing* |

The **delay in planting date** of a crop can be used to reduce the infestation of some annual weeds at the time of land preparation, allowing the first flushes and eliminating the seedlings mechanically or using a foliar or a non-residual herbicide. This technique is called "false planting", often used in vegetables seedbeds. Generally, the control strategy should be adapted to the prevailing flora, which should be known in advance as well as its biology. The delay in planting has proven very useful in combating the resistance of some species in winter cereals, such as *Lolium rigidum and Avena sterilis* (Gill and Holmes, 1997; Recasens *et al.*, 2001; Torra *et al.*, 2005). The results were not clear against the dicot species *Papaver rhoeas,* resistant to tribenuron-methyl and 2,4-D. Some reduction is observed with a planting delay, but it is not as effective when the weed seed bank is very large, since weed germination may occur up until early spring in Spain (Cirujeda, Recasens and Taberner, 2003). Vegetables transplanting has also been used traditionally to provide the crop with some advantage over weeds.

Another weed control measure is the **stimulation of the differential growth of the crop,** which can be attained normally with the application of fertilizers. The choice of when and where to apply fertilizers over the foliage is important to prevent the growth of competitive weeds. It has been observed that *Avena sterilis* has a higher absorption of N, P and K than does wheat, and the level of nitrates in soil may influence the competition. However, this is not the case when the competition is between barley and *Lolium rigidum*, where the crop is more effective (González Ponce, cited in Torner *et al*., 1999). In addition, it has been observed that the application of nitrates promotes dormant seed germination of some species (*Avena* spp.). The application of fertilizers well in advance of planting may be useful in reducing the emerged seedlings with one weeding.

A traditional, greatly used measure in several areas devoted to livestock, as in the Mediterranean arid zones, is **sheep grazing**, which takes advantage of available stubbles and possible autumn weed emergence in woody plants. This favours the disappearance or delay and elimination of some annual weed species. However, precaution should be taken that the sheep are not coming from areas with a high predominance of resistant weeds. The animals may defecate ingested viable weed seeds (e.g., *Lolium rigidum*). In pastures of mountains overgrazed by bovine, where the toxic species *Euphorbia polygalifolia* prevails, sheep grazing has been found very useful (Busqué *et al*., 2004). This example again indicates the need to diversify systems to avoid the problems of infestations with non-susceptible species.

Knowledge of biological characteristics of prevailing troublesome weeds enables the best selection of the most effective control methods (Table 8).

### *3.1.4 Physical methods*

Physical methods include mechanical and manual weeding, slashing, conventional and precision tillage and thermal weeding, as well as covers and mulching with plastics, papers or plant residues.

Manual weeding is the oldest method and practised worldwide, but it is a tedious operation demanding arduous labour in industrialized areas. However, its importance in prevention should also be mentioned for controlling weeds in the surroundings of the trees and early weed spots, or for eliminating low density infestations of resistant populations.

Mechanical slashing is an effective maintenance system in multi-annual forage and tree plants, as well as in ditches and sod. Generally, there is a need to combine it with other control measures. It is important to recall that weed flora may also adapt itself to slashing and cause a proliferation of trailing–habit species (*Portulaca oleracea, Stellaria media, Chamaesyce* spp., *Polygonum aviculare*) with high regrowth capacity (*Aster squamatus, Rumex* spp.). It is essential that resistant species be slashed before seed setting.

| **Attributes** | **Examples** | **Effective control method** | **Non-effective control method** |
|---|---|---|---|
| Grouped germination | *Lolium rigidum* | Planting delay<br>False planting<br>Crop shift | Sheep grazing<br>Mechanical cultivation |
| Gradual germination | *Abutilon teophrasti, Papaver rhoeas, Avena* spp. | Long fallow to provoke germination followed by elimination of emerged plants | Planting delay<br>False planting<br>Crop shift |
| High seed production | *Abutilon teophrasti, Papaver rhoeas*, Crucíferas | Slashing or grazing to avoid flowering<br>False planting | Crop shift in the same cycle |
| Dormancy and high seed survival in soil | *Abutilon teophrasti, Papaver rhoeas, Avena* spp.<br>Cruciferae | Long fallow to provoke germination followed by elimination of emerged plant | Ploughing with mouldboard to bury weed seeds |
| Dormancy and low or medium seed survival in soil | *Lolium rigidum, Bromus* spp. | Exhausting seed bank through tillage<br>False planting or fallow | No tillage, slashing, grazing |
| Life cycle similar to crop | Cereal-*Avena*, Maize-*Setaria*, Cotton-*Abutilon*, Tomato-*Solanum nigrum* | Crop shift<br>Planting delay | |
| Parasitic species | Orobanche in sunflower or faba beans<br>*Cuscuta* in alfalfa | Crop shift | Mechanical methods in general |

| | | | |
|---|---|---|---|
| Species of vegetative reproduction (tubers, rhizomes, bulbs) | *Cyperus rotundus, Oxalis* spp., *Sorghum halepense* | Mechanical methods to exhaust the plant underground reserves – frequent slashing and grazing: *Pigs for cyperus, Geese for oxalis* | Mechanical methods breaking vegetative organs |
| Species of trailing habit | *Stellaria media, Chamaesyce serpens, Portulaca oleracea* | Tillage, rod harrow | Slashing, grazing |

**Table 8: Methods of agronomical control recommended according to weed attributes**

### 3.2.4.1 Conventional tillage

For a long time, mechanical methods have been used with many types of implements, such as grill cultivators, spike or disc harrows, rotovators, plows. They are still a viable option in several crops. The time of weeding is important here to achieve the necessary effectiveness against the weeds. Due to concern over the effect of disturbing the soil structure and erosion caused by tillage, particularly when the soil is overturned, as well as its fuel consumption, there is a tendency to reduce tillage, by practising some vertical or shallow cultivation. This causes a weed flora change with infestations of species that are more common in steep banks (in Spain *Bromus* spp., *Vulpia* spp.) and an increased density of others adapted to the conditions of minimum tillage (e.g., *Lolium rigidum, Salsola kali*).

The use of implements have advantages and disadvantages, which should be known and assessed since certain types of implements are required in order to achieve the various goals according to the biological and weed growth stage (Tables 9 and 10).

| Biology | Goals | Tools | Tools not to be used | Examples |
|---|---|---|---|---|
| Annuals (seeds with long dormancy) | Dragging subterranean organs to the soil surface and break | Cultivator, rotovator | Mouldboard plough | Cruciferae |
| Annuals (with short dormancy) | Seed burial | Mouldboard plough | Shallow cultivator | *Bromus* spp. |
| Perennials (taproots or regrowth) | Breaking and exhausting the reserves | Rotovator, cultivator | Mouldboard plough | *Cirsium* spp. |
| Perennials (with soft rhizomes) | Dragging subterranean organs to the soil surface and exhaust the reserves | Cultivator | Rotovator | *Sorghum halepense* |
| Perennials (with flexible rhizomes) | Dragging to the soil surface | Cultivator, harrow | Rotovator, mouldboard plough | *Cynodon dactylon* |
| Perennials (tubers, bulbs) | Dragging subterranean organs to the soil surface and expose them to adverse conditions | Mouldboard plough, discs | Rotovator, cultivator | *Cyperus, Oxalis* |
| Hydrophyle perennials (with deep rooting) | Drainage | Chisel, subsolator | Rotovator, mouldboard plough | *Equisetum, Juncus, Phragmites* |

**Table 9: Tools recommended according to the control goals and biological characteristics of the species to control**

| Weed type/weed | Uncropped | | | | | Cropped | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | General | | | In the interrow | |
| | Subsolator | Moulboard plough | Discs | Chisel | Fresadora | Tine harrow | Harrow rods | Cultivator | Rotovator | Hilling |
| Seedlings | L | S | S | S | S | S | L | S | S | S |
| Young annuals | L | S | S | L | S | L | L | S | S | S |
| Adult annuals | N | S | S | L | S | N | N | S | S | S |
| Adult perennials | N | S | L | NL | R | NR | N | L | R | L |

**Table 10: Effect on weed flora of different farming implements according to its biology and development**

S: satisfactory action. L: limited action. N: no action. R: risk of weed spread.

Source: Ferrero and Casini, 2001

Rod flexible harrows are simple implements that have been accepted in ecological agriculture. They are able to weed in the interrows of crops, such as winter cereals, maize, beans, vetch, leeks, etc. at their early stages. Their tillage is shallow (up to 5 cm); annual weeds are pulled and exposed to the air effect. Their effect does not compact soil and has less risk of erosion than traditional tillage. They are very effective against seedlings of dicots in dry, semi-arid areas. The weed control is not complete since some mimetic crop species and perennials escape.

Their effectiveness greatly varies (20–95 percent) and depends on the weed stage and soil moisture. With small weeds, low stands and soil moisture, the effect improves. Sometimes a little effect from harrowing provides the necessary advantage to the crop over the weed, which is enough to achieve a good yield (Pardo *et al.*, 2004). Table 11 shows an overview of the effectiveness of different cultural methods.

| | Fallow | Mouldboard ploughing | Cultivator | Delayed planting | Tine harrow (1) |
|---|---|---|---|---|---|
| *Lolium rigidum* | Effective | Effective | Ineffective | Variable (2) | Insufficient |
| *Avena ludoviciana* | Variable (2) | Ineffective | Insufficient | Variable | Insufficient |
| *Papaver rhoeas* | Effective | Ineffective | Effective | Variable | Variable (2) |

**Table 11: Approximate effectiveness of some cultural methods in favourable conditions against resistant weeds in cereals of Northern Spain**

(1) Over the crop.

(2) Sometimes very effective.

Sources: Recasens *et al.,* 2001; Cirujeda, Recasens, and Taberner, 2003; and Pardo *et al*., 2004

There are several light implements, with new designs and materials, which enable rapid and precise weeding and cultivation.

### 3.2.4.2 Precision weeding

Another row weeding option is the use of mechanical methods. Since it is difficult to weed in the spaces near the crop plants, it is recommended to use precision implements, either with a tractor or with self-regulated implements. The main disadvantage of these implements is that they are not very selective. For this reason, it is necessary to make some adjustments according to the planning distance and the type of soil. The automatic driving or row detection systems allow maximizing the weeded area since they can approach the crop without any risk to it (91-95 percent), increasing the speed of the process and reducing its cost (Kurstjens, 1999).

At present, there are two companies of precision guidance systems (Eco-Dan and Robocrop Galford), which adjust the position of the weeding implement during the movement of the tractor.

One of the main advantages of precision weeding is that it can be integrated with other systems, avoiding the increase of herbicide selection pressure on the weeds, the main cause of herbicide resistance.

One of these implements is the rotative horizontal brush. The first description of this implement of a Swiss design, the Bärtschi brand, is from 1986 (Geier and Vogtmann, 1986), but data on its effectiveness is rare. It has been observed that plastic spikes of this implement are able to go as deep as 3-4 cm. (Floch, 2003). Its effectiveness is good against young weed seedlings, i.e., almost at 4-leaf stage, as reported by Netland *et al.* (1994), Székelyné (1994) and Radics and Székelyné (2002). The main disadvantage of this implement is that it requires training to achieve high selectivity.

- *Automatic precision guidance systems enable weeding with precision.*
- *There is a need to integrate precision tillage with other systems.*
- *The rotative brush, tooth and torsion weeder may provide selective weeding.*

The brush weeder implement with vertical adjustable brushes separated by lines and with its position angle (made by Thermec, Sweden) seems to be accepted by the scientific community, as discussed in several publications: Melander (1997) and Fogelberg and Gustavsson (1999). However, this model is no longer made due to economical problems and unsatisfactory field results. These vertical axis brushes are adjustable and precise, but difficult to find in the market. It is for this reason that horizontal axis brushes are more often used and provide acceptable effectiveness in horticultural areas (Pardo *et al*., 2005).

Other implements used during the last years in horticulture are the finger weeder and torsion weeder. In Northern Europe, the first has practically replaced manual weeding in ecological horticulture (Leinonen, Saastamoinen and Vilmunen, 2004). It consists of two rubber discs, that driven by other metallic discs, remove the soil close to the crop row.

#### 3.2.4.3 Night tillage

Photobiological control consists of conducting preparatory work both for planting at night, in complete darkness, and during the day, covering the implements from the light with opaque canvases, thus preventing the required light penetration to stimulate weed germination.

Several experiments have been carried out in northern Europe, compiled by Juroszek and Gerhards (2004), which, unfortunately, have provided bias results. This variability is related to the differential sensitivity of the species to light, soil moisture and temperature regimes (compiled by Cirujeda and Taberner, 2006). Before applying this method, it is important to consider the species of the soil seed bank. The effect of the treatment will greatly depend on the species present. Later, the many external factors may have an influence, resulting in very significant reduction in germination up to a non-effect. Since the cost of this operation in the darkness is low, especially for the implements, it would be reasonable to recommend it as a tool for reducing weed germination.

In conclusion, with respect to tillage practices, it is necessary to follow the best practices for mechanical weeding to reduce the disadvantages of this weed control system (Table 12).

**Best practices in mechanical weeding**

Good practices for mechanical interventions should be applied under optimal conditions, particularly as follows:

- choose the right implement according to the type of soil, planting distance and density;
- regulate the depth of the work, speed, inclination of teeth and other necessary adjustments, all this depending on the type of implement;
- avoid working in a parallel direction to the slope;
- ensure the suitable crop and weed stage. Avoid delays in the interventions. Generally, the effectiveness increases when treating young weed seedlings;
- content of soil moisture: Work the soil deeply after adequate moisture conditions. The soil surface should be dry to enable shallow cultivation: the weeds will have more difficulties to root;
- take into consideration the weather forecast after any labour and avoid mechanical control if rain is expected, since the weeds may root again easily.

**Table 12: Recommendations of best practices for mechanical weeding, emphasizing the right conditions for its implementation**

### 3.2.4.4 Thermal weeding

Another alternative to chemical weeding is fire weeding, i.e., the use of heat through burners for weed control. These methods were tested in the United States during the 1960s shortly before the expansion of herbicide use (Muzik, 1970). In the 1990s, interest turned to its use in ecological organic farming (Ascard, 1998), mainly in crop rows, replacing the traditional, direct herbicide spraying in conventional agriculture (Netland *et al.*, 1994). The mechanism of action of fire weeding is based on two effects: the direct one over the cell membranes affecting proteins and the indirect one causing dessication (Ascard, 1995).

Fire weeding shows a number of advantages compared to mechanical methods: it can be used on moist soil when other implements cannot be used; it does not alter the soil; it does not change its own structure; and it does not favour germination of new seeds. Another advantage is that it does not alter crop roots since the treatment is shallow. Regarding its cost, in Europe it is generally cheaper than hand weeding (Bond and Grundy, 2001).

Although thermal weeding provided satisfactory results in various horticultural crops (Ascard and Fogelberg, 2002; Radics, Gál and Pusztai, 2002; Tei *et al*., 2002; Raffaelli *et al.*, 2004), different authors have reported that the resultant germination is not inhibited and provided evidence that the emergence of some species is enhanced (Bond and Grundy, 2001). Ascard (1995) observed more *Poa annua* plants after thermal treatment and Netland *et al*. (1994) observed an increased stand of *Capsella bursa-pastoris* and *Chamomilla graveolens* after using the burner. Suso *et al*. (2003) also found more regrowth of *Cyperus rotundus* after using the burner in one of the years of their experiments.

A characteristic disadvantage of thermal weeding is the perception of hazard to those working with liquate petrol gases, which is obviously less safe than working with herbicides.

**Thermal weeding:**

- controls seedlings of annual species;
- does not alter the soil;
- works in moist soil;
- does not affect crop roots;
- does not leave residues.

But:

- it may burn crop leaves;
- the treatment should be repeated;
- it sometimes stimulates the emergence of perennial species;
- it consumes a great amount of energy;
- it seems to be hazardous.

In the literature, there is a wide margin of the required treatment intensity for fire weeding depending on the target species and their sizes (Ascard, 1995). Several dose-response curves have been obtained for species such as *Chenopodium album, Urtica urens, Chamomilla suaveolens, Poa annua, Capsella bursa-pastoris, Stellaria media, Senecio vulgaris* (Ascard, 1995), *Abutilon theophrasti, Amaranthus retroflexus* and *Echinochloa crus-galli*

(Peruzzi *et al.*, 1998). Whereas for most of the species the best effect is achieved by treating young small seedlings, *Echinochloa crus-galli* is more susceptible when the plant has developed several leaves. In addition, it was not possible to control *Poa annua* with any of the tested rates and tested stages of the weed. *Capsella bursa-pastoris* and *Chamomilla graveolens* regrow if treated in advanced growth stages (Ascard, 1995). It is possible to find data on the effect of thermal weeding in several dicots, most of which are susceptible to this treatment, and also in grasses, which are more difficult to eliminate. There are no references on troublesome perennials, e.g., *Cyperus rotundus*.

According to the studies carried out in laboratory conditions to determine the necessary rates of propane, the indicative values are 7–65 kg propane $ha^{-1}$ (Peruzzi *et al*., 1998) or 20–100 kg propane $ha^{1}$ (Ascard, 1995). In field trials, the values of consumption tend to be higher since the target plant species may be at different growth stage. Raffaelli *et al.* (2004) determined a consumption of 107.5 kg $ha^{-1}$, while in Aragon, 92 kg $ha^{-1}$ were used. Netland *et al*. (1994) applied 50 kg $ha^{-1}$ propane twice in each application.

Ascard (1995) studied the effect of reduced rates of fire weeding applied repeatedly against some weeds in different periods of time. He found that repeated applications every 3 or 13 days were more effective than those applied in within a few hours or minutes. This methodology may be useful for species tolerant to fire weeding and those that germinate or sprout slowly (as with *Cyperus rotundus*).

Notwithstanding the above, fire weeding has a contact action that is insufficient for the required weed elimination and should therefore be combined with other cultural or physical methods (Tei *et al*., 2002).

Some studies have recently been carried out on the use of water vapour as a thermal agent. Due to high energy consumption, this method requires more research.

**Solarization** can also be considered a physical method, which is based on the use of solar heating. It does not unfavourably alter the soil and does not leave residues; it is effective against nematodes and pathogens, and can stimulate the growth of the planted crop. Its major disadvantages are that it takes months to achieve higher effectiveness, which is often partial and only applicable in sunny zones of the world, and the problems associated with the use of plastic sheet and its disposal. Recently, biofumigation has been shown as a method of great interest for replacing the use of methyl bromide as a soil fumigant. This method consists of incorporating organic matter in soil for its decomposition and releasing of gases able to eliminate pathogens and weeds. The method is useful in hot areas, particularly for growing various crops in greenhouses.

#### 3.2.4.5 Plastic mulching

Another alternative to the application of herbicides in horticulture is the use of plastic black polyethylene covers, which bring various technical and environmental advantages. These include increased yields and quality, better weed and insect management, high efficiency of the use of water and mineral fertilizers and some prevention of erosion.

The main disadvantages of this technique are the cost of the plastic, its management and difficulties in collecting its residues after the crop harvest. In addition, some perennial species are able to sprout and perforate the plastic (e.g., *Cyperus* spp.) or may take advantage of small holes (*Convolvulus arvensis*), which make it necessary to apply a herbicide or to remove the weed mechanically. Another disadvantage of the black polyethylene sheet is that in hot summers or hot areas, the excessive heating of soil may affect the crops (Radics and Székelyné, 2002; Pardo *et al.,* 2005). In any case, the major disadvantage is the disposal of the plastic (Camacho, 2004 and Martín-Closas and Pelacho, 2004). In 2002, in the region of Ebro Valley, Spain (Navarra, Aragón and La Rioja) alone, plastic consumption was estimated at 2 131 tonnes. Generation of solid non-recyclable residue causes its accumulation in non-authorized dumps and the use of polluting practices by the farmers. The common practice of incorporating plastic into the soil is considered to cause a pollution load of 140 kg/ha/year (González, 2003). It is important to consider the accumulative effect, because degradation of polyethylene in the environment is low. Three hundred years are required to degrade a polyethylene sheet of 60 micras without additives (Feuilloley *et al.*, 2003). Another option is to burn the plastic, but it will also pose a problem of atmospheric pollution. The volume of plastic residues generated is so large that it poses the serious question of the sustainability of the crop system. It is also important to consider that these plastics for agricultural use contain heavy metals (e.g., 16,1 ppm Pb; 11,1 ppm Cu; 7,2 ppm Ni from our analysis).

The use of black opaque polyethylene should be differentiated from the transparent polyethylene for mulching. The first plastic sheet is used as a barrier to light for controlling weeds, while the second is for promoting early crop growth.

#### 3.2.4.6 The use of biodegradable plastics

Mulching with biodegradable polymers aims to solve two problems caused by the use of polyethylene mulching: the residues left in the field and savings in the consumption of non-renewable fossil resources.

The biodegradable polymers with better possibilities of use are those made from renewable resources of the agricultural sector (starch of different origin, plant fibres, plant oils, others).

Awareness of the scarcity of energetic resources in the 1970s promoted studies to develop biodegradable plastics (Griffin, 1994). The first plastic biodegradable sheets were a mixture of polyethylene with starch and polyesters of bacterial origin. Currently, there are 30 different types of biodegradable materials available in the market, some of which have the same characteristics and are as manageable as traditional plastics (Bastioli, Belloti and Gilli, 1990, and Bastioli *et al.*, 1993).

However, there are still problems to solve because of the low use of these materials. Their degradation is often excessive and sometimes insufficient. In 2000, in Spain, it is estimated than there were 118 000 ha under mulching with these materials, which still represents a very low proportion related to the total crop area (Papaseit, 2001).

The first problem is the cost of the biodegradable plastics available in the market, which is three to four times greater than that of conventional mulching (Bastioli, 2003; Gutiérrez *et al.* 2003). This suggests that in most of the crops, the use of these materials is considered *a priori* unfeasible from the economic point of view. The difference in cost can be reduced if the petrol price does not increase and the demand of this material increases, enabling the reduction of production cost (Martin-Closas and Pelacho, 2003). Weed control using biodegradable mulch is similar in its effectiveness to conventional mulching (86–93 percent with biodegradable sheets, and 97-100 percent with the conventional ones).

### 3.2.4.7 The use of paper

Paper is another interesting alternative to plastic soil cover. It is an economic, biodegradable material, which can be purchased and used in sufficient amounts for small- and medium-sized farms. Its greatest limitations are its placement by the machinery, which causes the paper to be broken easily, and its short life span due to soil moisture.

Previous research shows that various papers (Kraft of 90-200 $g/m^2$) can be used satisfactorily for weed control. Its effectiveness (77–96 percent) has been equal to polyethylene used for three months for growing processed tomato. Paper has shown to have excellent effectiveness against *Cyperus rotundus*, at a rate of 90-200 $g/m^2$. Here the weed is not able to perforate the paper layer. Paper biodegradation is also very satisfactory. It does not leave residues as in plastic mulching. Although the equipment has to be adjusted (tension reduced, microperforation avoided and installation speed reduced), its mechanical application is feasible. It is recommended to work with recycled paper whenever their heavy metal content is low.

In any case, it is necessary to combine knowledge on the biology of weeds, cultural methods such as the use of mulching paper and direct control in order to ensure that weed populations are kept at adequate levels (Bond and Grundy, 2001).

*Advantages of paper:*

- *it may control several weeds, including Cyperus;*
- *it is biodegradable;*
- *it does not retain soil moisture like plastic sheets;*
- *it regulates soil temperature;*

*Disadvantages of paper:*

- *its price may be high according to quality;*
- *it may not be always available;*
- *placement over soil is difficult.*

#### 3.2.4.8 The use of plant residues as soil cover for weed control

The use of any type of organic plant residue, including those derived from the industrial plant processing, e.g., sugarcane, coffee and rice husks, cereal straw, crusts and sawdust, has been suggested. In each case, it is necessary to test for the right amount and application. This method is appropriate for use in vegetables and trees.

The covers of harvest residues and other organic materials affect the germination, the survival, growth and the competitive ability of weeds. Generally, it seems that the toxic effect of the residues is higher against weeds with small seeds than those with big seeds. Since the seeds of most crops are up to three times bigger than those of weeds in competition, management of harvest residues offers a good opportunity for weed suppression (Liebman and Mohler, 2001).

The effect of these covers over the weeds can be classified as direct and indirect. The direct effects are those produced by the interaction of the covers with the weeds or their seeds, while indirect effects are caused by environmental modification where weeds grow due to the presence of the cover in the soil. In addition, the use of harvest residues as soil cover plays an important role in soil conservation.

#### 3.2.4.9 Direct effect of plant residues used as cover against weeds

*a) Physical barriers*

Plant covers are a physical barrier for the emergence of weed seedlings in soil. The type of cover (continuous or discontinuous) and the thickness and the hardness of the material used play an important function in its weed control effect. Logically, the higher the mass of the cover, the higher the cover in soil and therefore, the greater the effect against seedling emergence.

Another effect produced by cover over the weeds is limiting the access to light. The shade produced by the cover in the soil implies the impossibility for weeds to access the necessary sunlight for photosynthesis (Bilalis *et al.*, 2003).

There are successful examples such as trials done by Radics and Székelyné (2002), which indicate that rye straw as cover provides better results for weed control in tomato than does the use of herbicides.

Maize harvest residues are an interesting material for its use as cover for weed control. These materials have an excellent capacity to cover the soil: 2 tonnes/ha of the cover are enough to cover 30 percent of the soil surface (Erenstein, 2002). However, these values depend on the size of the residue components (leaves and stem) and the form of dispersal in the field.

Table 13 shows the effectiveness obtained with different treatments against weeds in a trial of tomato for processing. The achieved control using straw was scarce and insufficient for obtaining an acceptable yield (data unpublished).

| **Treatment** | **Yields (%)** | **Weed Control (%) (3)** |
|---|---|---|
| Polyethylene (15µ) | 100 | 78.1 |
| Unweeded control | 29.1 | 0.0 |
| Manually weeded control | 81.5 | 66.4 |
| Herbicide (2) | 71.4 | 42.3 |
| Mater Bi (biodegradable plastic 15µ) | 72.5 | 68.3 |
| Saikraft (brown paper 200 g/m$^2$) | 85.9 | 90.5 |
| Rice straw (10 t/ha) | 75.5 | 58.1 |
| Maize straw (10 t/ha) | 80.8 | 44.2 |
| Barley straw (10 t/ha) | 62.2 | 42.8 |
| Yields (t/ha) in the treatment of mulching with polyethylene and weed cover (%) in the unweeded control | 78.7 | 89.4 |

**Table 13: Average tomato yields (yield obtained with polyethylene as a reference) and weed control (1) (the unweeded control as a reference) obtained in different treatments and organic mulching in a trial conducted with tomato, Montañana, Spain, 2005 and 2006**

(1) The main weeds were *Cyperus rotundus, Portulaca oleracea*, *Chenopodium album* and *Digitaria sanguinalis*.

(2) The herbicide used was rimsulfuron (0,015 kg i.a./ha) in 2005 and rimsulfuron + metribuzine in 2006 (0,0125 kg a.i./ha + 1,75 kg a.i./ha).

(3) 63 days after transplanting.

*b) Allelopathy*

Many harvest residues used as covers show allelopathic effects on the weeds. Allelopathy, according to its original meaning, is the production of chemical substances from living plant tissues or in the process of decomposition, which cause inhibitory or stimulatory effects, directly or indirectly, over the neighbouring plants (Molisch, 1937, cited in Catizone and Zanin, 2001). Allelopathy, related to the negative effects on neighbouring plants, also involves chemical substances released by the plants, which are then transformed by the microorganisms (Liebman and Mohler, 2001).

The release of these allelochemicals may occur from living plants or from organic residues in decomposition. For this reason, the use of plant residues as cover has the potential to add this chemical effect to the physical ones. Allelopathy is a complex process influenced by various factors related to the plants or the material in decomposition, the soil, and the plants receiving the allelochemicals and meteorological conditions, among others. There are different mulching materials such as rice and rye straw containing allelochemical compounds that are able to inhibit weed germination and development. However, allelopathy may not only affect the weeds, but may obviously also affect the crop, i.e., it does not have physiological selectivity. For this reason, it has to be used with care.

#### 3.2.4.10 Indirect effects of plant residues used as cover for weed control

In addition to the direct effects mentioned, there are other indirect effects such as the impact produced in the weed population dynamics, especially in the long term. The use of organic cover for weed control is one of the ways to supply organic matter to the soil and it is widely known for the important role it plays in the definition of soil characteristics, hence the soil-weeds relationship. For example, it has been observed that soil incorporation of organic matter may reduce the pressure exerted by the weeds over crop production, particularly in vegetables (Liebman and Davis, 2000). However, it has been seen that the changes in organic crop management of produce increased weed diversity. Thus, weed management is a priority in these systems. This can be useful for combating resistant species.

In sum, the main **advantages** of using plant covers are: (i) weed control, particularly annual species; (ii) preservation of soil moisture, an attractive technique for agricultural crop production systems in arid and semi-arid zones; (iii) reduction of erosion, the reason for which this technique is widely recommended in soil conservation programmes; (iv) maintenance of the thermal regime of soil through the regulatory effect of temperature, since the amplitude of day and night variations are reduced; (v) supply of organic matter to the soil; (vi) carbon sequestration by the soil; (vii) recycling of materials that are normally treated as residues; and (viii) the favourable effect in general on microbial living organisms and soil fauna.

Nevertheless, the use of organic cover, particularly using harvest residues, has various important **disadvantages** that should be taken into account. From the economical point of view, the use of organic covers is relatively unattractive, especially if its short-term impact is measured. Transportation and application of this material in the field may also incur higher costs than those systems using plastic sheets. Placing the cover properly in the field is a difficult task demanding high labour. It is for this reason that various types of implements have been designed to mechanically apply the cover, for example, the one described by Schäfer, Väisänen and Pihala (2002).

*Organic mulching or using straw:*

- *control annual weeds;*
- *preserve moisture;*
- *reduce erosion;*
- *regulate soil temperature;*
- *provide organic matter to the soil;*
- *may favour some pests.*

Other disadvantages in the use of some harvest residues are their susceptibility to fire, especially when dry straw is applied. The population of rodents and slugs may also increase under cover, while some weeds may also become a problem (Zaragoza Larios, 2003). The latter is particularly important if the problematic species are perennials, which are normally less affected by the covers. It is also important to point out that the introduction of organic covers may also introduce some weed seeds normally mixed with the biomass of harvest residues. Seeds from the previous crops, e.g., maize, barley and others, may also germinate, which could cause the elimination of volunteers.

Finally, another disadvantage in cold areas is the lack of the necessary heat in the soil for growing crops such as tomato and pepper.

### 3.2.4.11 Conclusion

None of the alternative methods for the use of herbicides are a solution; their application requires integration into a diversified strategy. The technical agent should choose the method that is the most appropriate and adaptable to its environment, taking into consideration economical criteria and assessing possible advantages and disadvantages.

These methods may reduce the need of herbicidal use and help to reduce the selection pressure on the weeds and possible cases of resistance. Obviously, when these methods are applied, new problems may emerge.

## References on the integration of non-chemical methods in combating weed resistance


**Ascard, J.** 1995. Effects of flame weeding on weed species at different development stages. *Weed Research*, 35:397-411 pp.

**Ascard, J.** 1998. Comparison of flaming and infrared radiation techniques for thermal weed control. *Weed Research*, 38:69-76 pp.

**Ascard, J. & Fogelberg, F.** 2002. Mechanical intra-row weed control in organic onion production. Fifth EWRS Workshop on Physical Weed Control, Pisa, Italy, 11 – 13 March 2002.

**Bastioli, C.** (2003): Mater-Bi: Biodegradable Material for Various Applications, in Steinbuchel, A. (ed): "Biopolymers", Wiley-VCH.

**Bastioli, C., Belloti, V., Del Giudice, L. & Gilli, G.** 1993. Mater-Bi: properties and biodegradability. *Journal of Environmental Polymer Degradation*, 1(3):181-191 pp.

**Bastioli,C., Belloti, V. & Gilli, G.** 1990. *The use of agricultural commodities as a source of new plastic materials.* International Symposium on Biodegradable Packaging and Agricultural Films. Paris, France, 10-11 May.

**Baumann, D. & Kropff, M.** 1999. Intercropping to improve suppression of weeds. 11th European Weed Research Society (EWRS) Symposium, Basel, Switzerland, 18 June – 1 July 1999.

**Bilalis, D., Sidiras, N., Economou, G. & Vakali, C.** 2003. Effect of different levels of wheat straw soil surface coverage on weed flora in Vicia faba crops. *Agronomy & Crop Science*, 189: 233-241 pp.

**Bond, W. & Grundy, A.** 2001. Non-chemical weed management in organic farming systems. *Weed Research*, 41:383-405 pp.

**Busqué, J., Méndez, S., Martín, P., Mallavía, H., Fernández, O., Manrique, F. & Zaragoza Larios, C.** 2004. Eficacia de distintos métodos de recuperación de pastos de puerto invadidos por *Euphorbia polygalifolia*. Actas de la 45ª Reunión Científica de la Sociedad Española para el Estudio de los Pastos. Valladolid, Spain. 8 pp.

**Camacho, F., 2004.** Diferentes alternativas a la gestión de biomasa procedente de residuos vegetales. *Ponencia en el VI Congreso de la Sociedad Española de Agricultura Ecológica, Almería, Spain, 27 September – 2 October 2004*

**Catizone, P. & Zanin, G.** 2001. *Malerbologia*. Bologna, Italy, Patron Editore. 925 pp.

**Cirujeda, A., Recasens, J. & Taberner, A.** 2003. Effect of ploughing and harrowing on a herbicide resistant corn poppy (*Papaver rhoeas*) population. *Biological Agriculture and Horticulture*, 21: 231-246 pp.

**Cirujeda, A. & Taberner, A.** 2006. El control fotobiológico de malezas: revisión de una técnica controvertida**.** *ITEA,* 102 (1), 27-40 pp.

**CPRH** (Comité de Prevención de Resistencias a Herbicidas)**.** 2000. *La resistencia de las malezas a los herbicidas*. Lleida, Spain, Tríptico. SPV.

**Craig Stevenson, F., Légere, A., Somard, R., Angers, D., Pagean, D. & Lafond, J.** 1998. Manure, tillage and crop rotation: effects on residual weed interference in spring barley cropping systems. *Agronomy Journal*, 90: 496-504 pp.

**Erenstein, O.** 2002. Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications (review). *Soil & Tillage Research*, 67: 115–133 pp.

**FAO.** 2003. *Weed management for developing countries*, by R. Labrada. FAO Plant Production and Protection paper. Rome. (Available at: http://www.fao.org/docrep/006/y5031e/y5031e00.htm)

**Ferrero, A. & Casini, P.** 2001. Mezzi meccanici. Cap. 1. In P. Catizone & G. Zanin, coord. *Malerbologia*. Bologna, Italy, Patron Ed. pp. 251-278 pp.

**Feuilloley, P., César, G., Benguigui, L. & Grohens, Y.** 2003. Biodégradation des films de paillage en polyéthylene: Conjecture ou réalité? Colloque International – Produits biodegradable et environnement. Rouen, France, 20–21 May 2003.

**Floch, M.** 2003. Des solutions pour optimiser le désherbage. Suplemento de PHM-Rev. *Horticole*, 443: 6-8 pp.

**Fogelberg, F. & Gustavsson A.M.** 1999. Mechanical damage to annual weeds and carrots by in-row brush weeding. *Weed Research,* 39, 469-479 pp.

**GAP** (Growers action planner)**.** 2005. *Preventing herbicide resistance* (available at http://www.ezigrain.com.au). Consulted on 20 October 2005.

**Geier, B. & Vogtmann, H.** 1986. The multiple row brush hoe - A new tool for mechanical weed-control. *In* R. Cavaroll & A.v. El Titi, eds. *Weed control in vegetable production*. Rotterdam/Brockfield, Holland, A.A. Balkema.

**Gill, G.S. & Holmes, J.E.** 1997. Efficacy of Cultural Control Methods for Combating Herbicide-Resistant Lolium rigidum. *Pesticide Science*, 51: 352-358 pp.

**González, A.** 2003. Estado actual de la contaminación de suelos por materiales plásticos de acolchado y posibles soluciones en las distintas comunidades autónomas. Proceedings from Reunión de Materiales Biodegradables para acolchados en Horticultura, Murcia, Spain., 30 January 2003.

**Griffin, G.J.** 1994. *Chemistry and technology of biodegradable polymers.* Blackie, Glasgow, U.K.

**Gutiérrez, M., Villa, F., Cotrina, F., Albalat, A., Macua, J., Romero, J., Sanz, J., Uribarri, A., Sádaba, S., Aguado G. & Del Castillo, J.** 2003. *Utilización de los plásticos en la horticultura del valle medio del Ebro*. Dirección General de Tecnología Agraria. Informaciones Técnicas 130.

**Juroszek, P. & Gerhards, R**. 2004. Photocontrol of weeds. *Journal of Agronomy & Crop Science*, 190 (6): 402-415 pp.

**Kurstjens, D., Kownhoven J., Bleeker, P., Van der Weide, P., Ascard, J. & Baumann, D.** 1999. Recent developments in physical weed control. 11th European Weed Research Society (EWRS) Symposium, Basel, Switzerland, 18 June–1 July 1999.

**Leinonen, P., Saastamoinen, A. & Vilmunen, J.** 2004. Finger weeder for cabbage and lettuce cultures. Sixth Workshop on Physical and Cultural Weed Control, Lillehammer, Norway, 8-10 March 2004**.**

**Liebman, M. & Davis, A.** 2000. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Research*, 40:27-47 pp.

**Liebman, M. & Mohler, C.** 2001. Weeds and the soil environment. *In* M. Liebman., C. Mohler & C. Staver, eds *Ecological management of agricultural weeds*. Cambridge, United Kingdom, Cambridge University Press.

**Martín-Closas, L. & Pelacho, A.M.** 2004. Los acolchados biodegradables como alternativa a los acolchados de papel y de polietileno en un sistema de producción ecológica de tomate. VI Congreso de la Sociedad Española de Agricultura Ecológica (SEAE), Almería, Spain, 27 September– 2 Octuber 2004. 1559-1572 pp.

**Martín-Closas, L., Soler, J. & Pelacho, A.M.** 2003. Effect of different biodegradable mulch materials on an organic tomato production system. In *Biodegradable materials and natural fiber composites*. KTBL Darmstadt. *Schrift*, 414:78-85 pp.

**Melander, B.** 1997. Optimization of the adjustment of a vertical axis rotary brush weeder for intra-row weed control in row crops. *J. agric. Engng. Res,* 68: 39-50 pp.

**Muzik, T.J.** 1970. *Weed biology and control.* New York, USA, McGraw-Hill. 273 pp.

**Netland J., Balvoll, G. & Holmoy, R.** 1994. Band spraying, selective flame weeding and hoeing in late white cabbage. Part 2. *Acta Horticulturae*, 372: 235-243 pp.

**Papaseit, P.** 2001. Plásticos agrícolas en España. *Revista Horticultura*, 156: 22-36 pp.

**Pardo, G., Suso, M., Pardo A., Anzalone, A., Cirujeda, A., Fernández-Cavada, S., Aibar, J. & Zaragoza Larios, C.** 2005. *Different weed control systems in tomato*. 13rd EWRS Symposium, Bari, Italy, 19-23 June 2005.

**Pardo, G., Villa, F., Aibar, J., Fernández-Cavada, S. & Zaragoza Larios, C.** 2004. Control mecánico de malezas en cultivo de cebada. *ITEA*, 100V (1): 18-33 pp.

**Peruzzi, A., Di Ciolo, S. & Raffaelli, M.** 1998. Effects of flame weeding on velvetleaf (*Abutilon theophrasti* L.) common amaranth (*Amaranthus retroflexus* L.) and cockspur grass (*Echinochloa crus-galli* L.). Proceedings of the AgEng 1998 International Conference on Agricultural Engineering, Oslo, Norway, 24–27 August 1998.

**Radics, L., Gál, I. & Pusztai, P.** 2002. Different combinations of weed management methods in organic carrot. 5th EWRS Workshop on Physical Weed Control, Pisa, Italy, 11 – 13 March 2002. 137-146 pp.

**Radics, L. & Székelyné, E.** 2002. Comparison of different mulching methods for weed control in organic bean and tomato. 5th EWRS Workshop on Physical Weed Control, Pisa, Italy, 11 – 13 March 2002, 192-204 pp.

**Raffaelli, M., Filippi, F., Peruzzi, A. & Graifenberg, A.** 2004. Flaming for intra-row weed control in Globe Artichoke. 6th Workshop on Physical and Cultural Weed Control, Lillehammer, Norway, 8-10 March 2004**.** 139-142 pp.

**Recasens, J., Planes, J., Briceño, R. & Taberner, A.** 2001. Cultural methods to control herbicide resistant *Lolium rigidum* populations in Catalonia, Spain. 18th COLUMA Conference. Toulouse, France, 5-7 December.

**Romic, D., Romic, M., Borosic, J. & Poljak, M.** 2003. Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. *Agricultural Water Management,* 60(2):87-97 pp.

**Runham, S.R., Town, S.J. & Fitzpatrick, J.C.** 2000. Evaluation over four seasons of a paper mulch used for weed control in vegetables. *Acta Horticulturae*, 513:193-201 pp.

**Schäfer, W., Väisänen, J. & Pihala, M.** 2002. Technique of green mulch spreading. Study report. *Vakolan tutkimusselostus*, 79 pp.

**Suso, M., Pardo, A., Hernández, J., Villa, F., Fernández-Cavada, S. & Zaragoza Larios, C.** 2003. *Comparación de diferentes sistemas de escarda en cultivos de tomate*. Congreso 2003 de la Sociedad Española de Malherbología, Barcelona, Spain, 4–6 November, 156-159 pp.

**Teasdale, J. & Mohler, C.** 2000. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science*, 48:385-392 pp.

**Tei, F., Montemurro, P. Baumann, D.T., Dobrzanski, A., Giovinazzo, R., Kleifeld, Y., Roch,a F., Rzozi, S.B., Sonseovic ,T., Simoncic, A. & Zaragoza Larios, C.** 2002. Weeds and weed management in processing tomato. 5th World Congress on the Processing Tomato. 8th ISHS Symposium on Processing Tomato, Istanbul, Turkey, 8–10 June 2002. *Acta Horticulturae*, 613, 111-120 pp.

**Torner, C., Aibar, J. Bellostas, A., De Lucas, C., Esparza, M., Fernández Quintanilla, C., González Andujar, J.L., González Ponce, R.,**

**Izquierdo, J., Navarrete, L. & Zaragoz,a C.** 1999. Conclusiones de los trabajos sobre la competencia de malezas con los cereales de invierno en España. Actas Congreso Soc. Esp. *Malherbología. Logroño*.

**Torra, J., Ribalta, M.M.,Taberner, A. & Recasens, J.** 2005. El manejo de barbechos en el control de poblaciones de malezas resistentes a herbicidas. Cap. 64. *Malherbología Ibérica y Magrebí: soluciones comunes a problemas comunes*. Collectanea 93 Univ. de Huelva, Spain, 425-430 pp.

**Valverde B. & Gressel J.** 2006. Dealing with evolution and spread of Sorghum halepense glyphosate resistance in Argentina. Report to SENASA 86 pp. (Available at: http://www.weedscience.org/paper/Johnsongrass%20Glyphosate%20Report.pdf

**WRAG** (Weed Resistance Action Group Guidelines)**.** 2003. *Managing and preventing herbicide resistance in weeds.* London, UK. (available at http://www.hgca.com/cms_publications.output/2/2/Publications/Publication/Managing%20and%20preventing%20herbicide%20resistance%20in%20weeds.mspx?fn=show&pubcon=850).

**Zaragoza Larios, C. & Delgado, I.** 1996. Un ensayo sobre coberturas vegetales en viña. *ITEA,* 17: 404-405 pp.

**Zaragoza Larios, C.** 1999. Manejo de la flora arvense en programas de producción integrada. 6º Symp. Nal. Sanidad Vegetal, Sevilla. Congresos y jornada 48/98. Consejería de Agricultura. Junta de Andalucía, 20- 22 Enero. pp. 39-51.

**Zaragoza Larios, C.** 2003. Weed management in vegetables. *In* R. Labrada, ed *Weed management for developing countries*. Addendum 1. FAO Plant Production and Protection paper. Rome, FAO. (Available at: http://www.fao.org/docrep/006/y5031e/y5031e0b.htm#bm11)

### 3.3 Integrated weed management

To prevent resistance, weed management activities should be planned for the medium and long term, but not annually, integrating various weed control strategies. Strategies should be applied as diversely as possible in order to minimize the risk of resistance.

It is important to take into account that the repetition of any control method, be it mechanical, cultural or chemical, usually results in the adaptation of a weed species. The best tool for management is the frequent shift of strategy.

Integrated weed management (IWM) is considered the most effective way to control weeds, which is based on the coordinated use of different strategies in the medium and long term. There are other definitions, for example:

- the combined use of all possible control methods so that some are reinforced with others, taking advantage at the same time of the weakness of the weeds;
- a long-term strategy including a combination of various methods, direct and indirect, to keep weed infestation below the admissible economic threshold (Zwerger, 1996).

In all these cases, a maximum of possible control methods should be combined, which may accordingly provide sustainable weed control on time.

Interest in the application of integrated management is shown by several publications, for example Fernández-Quintanilla, Garrido and Zaragoza (1999).

A programme of integrated management should be (adapted from CRC, 2006):

- flexible, able to respond to the crop requirements at the time of its application;
- based on a good understanding of the biology of target weed species;
- adapted to the farm conditions: climate, soil, history;

- linked to the economical goals of long-term farming;
- inexpensive (with a good cost-benefit ratio) in the short term.

Table 14 shows some three examples of integrated weed management cases.

| Species | ***Lolium rigidum*** | ***Papaver rhoeas*** | ***Amaranthus retroflexus*** |
|---|---|---|---|
| Resistance to the herbicide | Various fops, dims and ureas. | 2,4-D and tribenuron-methyl. | Atrazine |
| Affected crop | Dry winter cereal. | Dry winter cereal. | Irrigated maize |
| Possible pre-planting control methods | Planting delay and mechanical control of emerged weeds or use of a broad-spectrum herbicide. | ---- | False planting and control of emerged weeds, mechanically or using a broad-spectrum herbicide. |
| Possible control methods during the crop cycle | Slashing or grazing before plant flowering. | Mechanical control (harrow with flexible spikes). | Mechanical control (harrow with flexible spikes). |
| | Use of a herbicide from a different HRAC group, active over the resistant species. | Use of a herbicide from different HRAC group, active over the resistant species (for example, mixed with bromoxynil). | Use of a herbicide from a different HRAC group, effective over the resistant species (e.g., MCPA). |
| | Crop rotation: rape, sunflower. Possible use of grass killers from different HRAC groups. | Crop rotation: rape, sunflower. | Crop rotation: winter cereal, rape, sunflower, alfalfa. |
| Possible control methods after crop | Fallow and mechanical or chemical control with a broad-spectrum herbicide. | Fallow and mechanical or chemical control with a broad-spectrum herbicide | Elimination of flowered plants in wings and steep banks. |
| | Till with mouldboard plough (maximum | Till with mouldboard | |

| | | | |
|---|---|---|---|
| harvest | every two years). | plough (maximum every five years). | |
| | Cleaning the harvester to avoid weed spread. | | |
| | Use of certified seed free of weed seeds. | Use of certified weed-free seeds | |
| | Burning stubbles wherever possible. | | |
| | Surveillance of weed infestation. | Surveillance of weed infestation. | Surveillance of weed infestation. |

**Table 14: Three examples of resistant weeds and possible methods for integrated management**

# 4. DISSEMINATING INFORMATION TO FARMERS ON HERBICIDE RESISTANCE

## 4.1 Information compilation

In order to prevent resistance, it is important to disseminate the guidelines to all stakeholders involved. Dissemination should be undertaken according to local conditions and the people working in this area. It is important to involve and raise awareness of all those who could cause resistance through an inappropriate or improper use of the herbicides.

Generally, this work has been carried out by national working groups, where various representatives of the aforementioned classes participate. The working group in Spain, which belongs to the Spanish Weed Society, has achieved good results.

The main information to include is:

- the fact that there is a problem of resistance;
- a descriptions of the cases of how resistance has developed and the extent of the problem;
- an explanation of applicable solutions.

It should be pointed out that resistance is a localized problem affecting applied herbicides and a solution should be found for the correct use of herbicides within an integrated weed management approach in the medium and long term.

The information should be compiled from field surveys consisting of weed sampling and testing of resistance in laboratory conditions.

It is also useful to gather information through regular weed surveys, such as the following :

- the Survey of the CPRH (2000);

- the Survey of the Working Group on Weed and Herbicides of the Spanish Protection Services (2005);
- the assessment of the extent of *Sorghum halepense* resistance to glyphosate in Argentina (Valverde and Gressel, 2006).

In all these examples, the magnitude of the problem should be quantified and the herbicides involved should be identified. It is difficult to assess the real extent of the problem since resistance directly affects populations in fields. Therefore, the number of affected fields and estimated area are occasionally given.

### *4.1.1 Survey to estimate the spread of herbicide-resistant weeds in winter cereal in Spain (2002)*

***Who promotes the survey?***

The CPRH is a working group consisting of various representatives from the agrochemical companies credited in Spain, universities and non-profit public or private institutions, departments of central or autonomous public administrations. It aims at facilitating the prevention and the control of herbicide resistance.

***The objective of this survey***

In winter cereals, the resistance of some weed species is a well known fact. Since this is a dynamic problem, its magnitude changes with time. This explains why the survey is proposed as a complement to projects for assessing resistance and quantifying the area of winter cereals in Spain affected by the one or more weeds that are resistant to one or more herbicides.

***Who will answer the questionnaire?***

This questionnaire is sent to the representatives of the main companies of phytosanitary products.

***How to fill in the questionnaire***

The data should be indicated separately for each province where your products are sold/distributed. If this is an area or a region inside the province, kindly indicate which one. Write the number of approximate fields you know are infested by resistant species to herbicides of different groups. Only provide the names of the products you represent and distribute. Kindly indicate whether the weeds are resistant to more than one herbicide. Use as many leaves as necessary for your response.

| | |
|---|---|
| Enterprise you represent | |
| Area of distribution | |
| The most sold herbicides in the area | |
| Is there any crop rotation in the area? | |
| Is ploughing practised? (mouldboard) | |

For further comments, do not hesitate to contact CPRH:

http://www.plantprotection.org/hrac/Cindex.cfm?doc=Spanish_Resistance.htm

*Avena* spp. (Wild oat, cugula)

| Province | Region/ zone/ locality | Imidazolinones (1) | | Fops, dims (2) | | Ureas (3) | | Others (specify) | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

(1) The herbicides Assert, Savex, Chacal belong to this group.

(2) The herbicides Topik, Colt, Iloxan, Puma, Gamo, Splendor belong to this group.

(3) The herbicides containing the active ingredient chlortoluron or isoproturon belong to this group.

*Lolium rigidum* (Vallico, luello, margall, fenaç etc.)

| Province | Region/ zone/ locality | Fops, dims (4) | | Ureas (5) | | Sulfonylureas (6) | | Others (specify) | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

(4) The herbicides Topik, Colt, Iloxan, Gamo, Splendor belong to this group.

(5 The herbicides containing the active ingredient chlortoluron or isoproturon.

(6) The herbicides Glean, Belure belong to this group.

*Papaver rhoeas* (Amapola, ababol, rosella, roella, etc.)

| Province | Region/ zone/ locality | Sulfonylureas (7) | | Auxins (8) | | HBN's (9) | | Others (specify) | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) | No. of fields | Area (ha) |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

(7) The herbicides Granstar, Posta belong to this group.

(8) The herbicides containing 2,4-D, MCPA, MCPP, diclorprop or dicamba belong to this group.

(9) The herbicides containing the active ingredients ioxynil, bromoxynil belong to this group.

### *4.1.2 Questionnaire on herbicide resistance, Aragon 2005*

**Name:** __________________________________________________

**Working area:**_____________________________________________

1. Have you ever heard about resistance to herbicides?

☐YES ☐NO

2. Do you think that there are problems of weed resistance to the herbicides that are typically used in your area?

☐YES ☐NO ☐Do not know

3. Do you think, on the contrary, that there is no resistance but, rather, misapplications?

☐Resistance ☐Bad applications ☐Both

4. In which crops?

5. When did it start?

6. Which weeds? (Please, indicate common or scientific name, if known.)

7. To which herbicides?

8. In which municipalities?

9. Do you think that the problem is widespread or localized?

☐Widespread ☐Localized

10. What do you think is the approximate area affected?

☐ Surrounding areas, spots

☐1-10 ha ☐10-50 ha ☐> 50 ha

11. How do you solve problems of resistance? Have you taken any measures? Which ones?

12. Do you think this is a serious problem?

13. Do you think that farmers have enough information to address these problems?

14. Do you familiar with the booklets edited by CPRH?

☐YES ☐NO

15. Other relevant comments on this issue:

**Once the questionnaire is completed, please send it by e-mail.**

Assessment of the extent of the problem of glyphosate-resistant *Sorghum halepense* in Argentina (2006)

## FORM FOR NOTIFYING AND DETECTING RESISTANT PESTS

## The case of Johnsongrass (Sorghum halepense) resistance to glyphosate

### 1. COLLABORATOR

Name: ________________________________________

Activity: ________________________________________

Producer ☐ Researcher ☐ Adviser ☐ Professional ☐

Laboratory ☐ Company ☐ Other ☐

Institution/Company: ________________________________________

Postal address ________________________________________

Telephone: ________________________________________

E-mail: ________________________________________

2. **IDENTIFICATION SITUATION**

| **2a) If the observation was done in the field** | |
|---|---|
| Date | |
| Geographical localization, affected plot (indicate province, department, locality) | |
| Site according to GPS (if available) | |
| Name of the farm | |
| Reference to access to the plot/farm | |
| Fallow/crop situation (phenological stage) | |
| Affected area in hectares (estimated) | |
| Weed distribution in the plot (erase what is irrelevant) | ***Spots generalized*** |
| Weed height | |
| Preceding crop | |
| Applied herbicides to the affected crop (indicate the active ingredient, form, rates and equipment) | |

**Please send the completed form by e-mail.**

### 4.2 Sources of information

From the academic point of view, there are numerous sources of information, several books and publications, some of them provided in the references below as well as online. Some websites of interest are:

- www.weedscience.com
- www.plantprotection.org
- www.weeds.crc.org.au
- www.pesticides.gov.uk
- www.semh.net

However, the most direct sources of information are the local surveys and questionnaires, as previously described.

### 4.3 Channels for disseminating information

The most usual channels are:

- technical days or sessions;
- working groups;
- leaflets;
- Internet.

Technical Days are an excellent opportunity to disseminate information on resistance. These sessions should not be long, half a day or one day, and should be flexible, direct, lively and highly participative. For this reason, it is essential that there be active participation of local agents who know the idiosyncrasies and the characteristics of the area in which the information will be distributed.

Full or partial technical days conducted in the field with a modest number of participants are very useful. The best scenario would be one in which the results where no palliative measure is taken are compared twith proper management of the population through of an integrated programme.

The working groups have a more technical character. They should not be excessively long and time should be allowed for an in-depth treatment of the issues of resistance. According to the idiosyncrasies of the area or region, it would be reasonable to invite a recognized expert.

Within the activities of the Spanish CPRH, information dissemination has had special importance as well. Moreover, experience acquired has shown that the organization of meetings with participants from the local venue is very important. These participants should be from Research Services, such as Plant Protection Services, the herbicide industry and distributors, as well as farmers affected by the problem.

Through brief and concrete interventions, the participants gladly receive the information coming from heterogeneous groups, who work in a coordinated manner, with common interests and geographical origin.

Leaflets are another useful channel of communication. They should be colourful and graphic. It is advisable to distribute them by attaching other information relevant to farmers, for example, invoices or technical information from the administration or from distribution channels of phytosanitary products.

Finally and no less important, Internet can be used to gather and communicate information.

## 4.4 Chart on information dissemination

An agenda for a meeting on herbicide resistance prevention is given below.

The timetable should be adapted to the customs and local habits as well as the duration of the talks.

| Time | Theme |
|---|---|
| 10:30-11:00 | Welcome speech by the authorities and local personalities |
| 11:00-11:10 | Background on the local working group |
| 11:10-11:30 | Status of herbicide resistance in the area or the country |
| 11:30-12:00 | Management of resistant weed populations of interest |
| 12:00-12:15 | Talks. In each presentation, time should be allotted for questions and answers |
| 12:15-12:30 | Brief break |
| 12:30-13:00 | Lecture on local problem, presented by an expert or authority on the area |
| 13:00-13:30 | Lecture on the theoretical bases of resistance, presented by a representative of a research centre or university |
| 13:30-13:45 | Activities for the year |
| 13:45-14:00 | Talks and conclusion of the day. In each presentation, time should be allotted for questions and answers |
| 14:00 | Refreshments |

# 5. A HUNDRED QUESTIONS ON RESISTANCE AND EXERCISES FOR TECHNOLOGY TRANSFER ON HERBICIDE RESISTANCE

This final chapter compiles questions and answers for better understanding of this material and as a guidance for future work on herbicide resistance to be organized.

These questions have been organized in five groups:

- General issues;
- Herbicides;
- Genetically modified crops;
- Non-chemical methods;
- Integrated management.

Questions were raised during the preparation of this book. In some cases, there might be issues not explained previously. As a rule, most of the issues have been discussed in the previous chapters.

The answers can be short, varied or full. They only serve for clarification and further group discussion.

It is hoped that this exercise on resistance will be useful for a better understanding of the phenomenon.

## 5.1 Questions on general issues

### *1. Is the problem of herbicide resistance really important?*

It depends: it is not as important as other problems faced in agriculture, such as economic ones, e.g., low prices of the produce. The problem may seem minor if one estimates the area affected. However, this is an increasingly important problem, which reduces the value of cheap and environmentally acceptable herbicides. The problem may also hinder the cropping process (Chapter 1.3).

2. ***What is the difference between a susceptible, non-susceptible and resistant plant?***

*Susceptible plant:* a plant that dies under the effect of the application of a herbicide at normal rates and in favourable conditions.

*Non-susceptible plant* (also called *tolerant*)*:* a plant that does not die from the application of a herbicide at normal rates in any field.

*Resistant plant:* a plant that does not die from the application of a herbicide, which in the past used to be effective at normal rates and in favourable conditions on the field (Chapter 1.4).

3. ***What is the difference between flora inversion*** **(also called "shift flora") and** ***resistance?***

Both cases are a response to the repetitive use of a herbicide. Flora inversion shows how tolerant species never controlled by the herbicide replace the space left free by susceptible species. In resistance, there is no replacement of the species, but previous susceptible populations are not killed by the herbicide used (Chapter 1.5).

4. ***What is the difference implied by resistance that is coded by a dominant gene or by a complex of recessive genes?***

Coded resistance by a dominant gene is expressed both in heterocygotic and homocygotic dominant individuals, so the resistance is transmitted quickly. The resistance will be expressed as present or absent with no gradation. Concerning a complex of recessive genes, the resistance will be expressed less and there will be more cases of gradation.

***5. What is the initial frequency of resistant individuals?***

This is the total number of plants of the same species divided by the number of resistant plants in the field. Normally, natural untreated populations should show a low frequency (e.g., estimated at $10^{-6}$ or less).

***6. Is a resistant population a group of non-susceptible individuals?***

No, a non-susceptible individual belongs to a species that has never been affected by the herbicide used, while the resistant individual belongs to a species killed in the past by the herbicide used in normal conditions of application (Chapter 1.4).

***7. Is herbicide resistance always a problem in previously susceptible populations?***

No. In the case of resistance to triazines, it is common to find resistant populations of smaller plants that are less reproductive or with less pronounced fitness than in the susceptible populations. The already resistant individuals show the same ability for survival and vigour as susceptible ones (Chapter 2.4).

## 5.2 Questions on herbicides

***8. What are the main problems caused by improper herbicide use?***

It can generate weed resistance, shift flora and pollution in the environment.

***9. How many years will it take before the development of herbidice resistance?***

It depends on the natures of the herbicide, its use and the weed species involved. Herbicides of groups A, B and C pose the maximum risks, meaning that their repetitive use may cause problems of resistance in four years. If the use is not different and is only based on the herbicide application, resistance may develop quickly. There are species that generate resistance more quickly than others (e.g., *Lolium rigidum, Amaranthus* etc.) (Chapter 2).

***10. How can I know whether there is resistance in my field?***

First, one must be sure that there was no herbicide misapplication. Moreover, the resistant species must have an inheritable capacity (Chapter 2.1).

***11. Which tests are available for detecting resistance?***

There are tests for seed germination on different media treated with the herbicide. Others consist of using powdered new plant tissues that have survived the application of the herbicide of interest. There are other specific tests, for example, the one based on detecting the chlorophyll degradation by fluorescent emissions used for inhibitors of photosynthesis or biotechnological procedures used to distinguish the plants showing a genetic mutation (Chapter 2.1).

***12. What is the importance of knowing the history of the field where resistance is suspected?***

In general, it is essential to observe if the herbicide effectiveness has decreased against any particular species.

***13. What are the main details to check in the field's history?***

The quality of the applications – including target plant height, climatic conditions before, during and after the treatment – is important to know for comparing efficacy in different years. It is equally important is to know the herbicide efficacy in neighbouring plots.

***14. What is the importance of detecting the first spots of resistance in the field or the farm?***

The earlier that resistance is detected, the better its further development can be controlled (Chapter 2.1).

***15. How is resistance in the field prevented?***

This can be done by alternating and diversifying the weed control methods and management (Chapter 3).

***16. What is the optimal rate of the herbicide to be used?***

The optimal rate is the minimal one able to provide the best control.

***17. Can a new herbicide emerge to solve the problem of resistance?***

Yes, but the solution may not last long if the herbicide is used repeatedly (Chapter 3).

***18. If you stop applying a herbicide due to a resistance problem, is the resistance reduced?***

Resistance is inheritable so there will always be seeds of the resistant plant in the field. The resistance may be reduced but not eradicated (Chapter 2).

***19. What is the difference between mixture, sequence and rotation in herbicide use?***

*Mixture:* two or more active ingredients applied at once;

*Sequence:* two or more herbicide active ingredients applied one after another in a certain period of time, generally during the cycle of the crop;

*Rotation:* two or more herbicide active ingredients applied in different crop periods (Chapter 3.1.2).

***20. What are the mechanisms of herbicide resistance?***

The most frequent mechanisms are mutation in the site of action, accelerated metabolism, a lack of absorption and vacuole confinement (Chapter 2.2).

***21. Are there glyphosate-resistant weeds? Why has the resistance developed so late?***

In 2006, there were 12 different weed species resistant to glyphosate. The main explanation of the delay in resistance development is that the initial frequency of resistant plants to this herbicide was low (Chapter 1.3).

***22. What measures can be adopted to delay resistance to glyphosate in annual and perennial weeds?***

To reduce the frequency of glyphosate applications, alternate with other control methods or with the application of other herbicides (Chapter 1.4).

***23. What is "herbicide selection pressure"?***

It is the effect of herbicide treatment on weed populations in the field that are able to select resistant biotypes (Chapter 2.3).

***24. What factors intervene in herbicide selection pressure?***

The factors are the type of herbicide, its formulation and frequency of application; the characteristics of target weeds, their emergence, the longevity of weed seed bank in the soil and the application of other control alternatives that may mitigate this pressure.

***25. Can farmers modify the herbicide selection pressure?***

Yes, farmers may reduce the selection pressure by using the herbicide less often and implementing other control alternatives (Chapter 2.3).

***26. Have all herbicides the same selection pressure? Do all herbicides cause problems of resistance?***

Selection pressure does not depend on the efficacy of the applied herbicide and its correct rate of application. The initial frequency of resistant genes in any weed varies according to the herbicide applied and is the main cause for the differences in resistance development (Chapter 2.3).

***27. Herbicides are classified in different groups according to the established HRAC criteria. A letter is assigned to each group. What is the meaning and application of this classification?***

The herbicides belonging to the same group will have similar mechanism of action. This means that a weed resistant to one of these herbicides may also easily be resistant to any other in the same group (crossed resistance), while it may be susceptible to herbicides of other groups (unless there is multiple resistance). Concerning herbicide rotation, the use of herbicides from different HRAC groups is recommended in order to reduce the risk of resistance (Chapter 3.1.1 and Table 4).

***28. Is the WSSA classification the same as HRAC? Is this used similarly?***

They are the same groups but with different notations. They are used in the same manner.

***29. When a weed becomes resistant in the field, can we continue using the same herbicide mixed with others to mitigate the problem?***

No, the use of this herbicide should be avoided even when mixed with other herbicides because its selection pressure may be increased, thus exacerbating the problem (Chapter 3.1).

***30. What are the consequences of the application of two or more herbicides mixed for weed control?***

If the mixture controls the target problematic species, the resistance will be delayed since it is not likely that the weed may be able to develop resistance to two different modes of action (Chapter 3.1.2).

***31. What delays resistance to a greater extent, the use of a herbicide mixture or crop rotation?***

Crop rotation. It may change the crop cycles and reduce the resistant weed infestations. It also enables the use of other herbicides, which is also effective against the resistant weed (Chapter 3.1.2).

***32. What aspects should be taken into account in a correct herbicide application?***

The herbicide should be applied under favourable climatic conditions – temperature, soil moisture, absence of wind – and correct rates of uniform application – never below the recommended rate, applied at the right weed and crop phenological stages, and no later than the recommended ones.

***33. Is herbicide persistence a risk factor in developing resistance?***

Yes, it acts on the selection pressure during the period when it is still active (Chapter 3.1).

***34. Can herbicides replace all other non-chemical control methods?***

No, they need to complement each other and should be part of integrated management.

## 5.3 Questions on genetically modified crops

***35. Genetically modified herbicide-resistant crops are sometimes mentioned. Is this terminology correct?***

To some extent, yes. However, it is necessary to differentiate it from weed resistance caused by the incorrect use of a herbicide. In the case of genetically modified crops, the process is controlled by humans.

***36. Can genetically modified crops (GMCs) bring any benefit to weed control?***

Yes, the associated herbicide with the modified crop should be effective against the resistant weeds; this enables the use of alternative control option (Chapter 3.1.4).

***37. How can planting a trangenic crop influence the emergence of resistant weeds?***

Transgenic herbicide-resistant crops may assume a repeated use of the associated herbicide, which poses a risk. If the herbicide is inexpensive, its use will be encouraged to improve crop profitability (Chapter 3.1.4)

***38. In weed control, GMCs are understood as "a double-edged sword". Why is this so?***

On the one hand, they provide an opportunity to use a different herbicide to control herbicide-resistant weeds, but, on the other, its inadequate and improper use (late applications, repeated over time or at too-low rates) may cause resistance to the new herbicide in use. It should therefore be used with care.

***39. Can herbicide resistance develop in fields where genetically modified herbicide-resistant crops are grown?***

Yes, some herbicide-resistant weeds may emerge if the same herbicide is used repeatedly.

***40. Can pollen flow from genetically modified herbicide-resistant crops create a "superweed", which would be difficult to control chemically?***

No, not in the sense that it could not be controlled with any herbicide. However, weeds closely related to the transgenic crops (for example, weedy rice in transgenic herbicide-resistant rice) may outcross and becomes resistant.

***41. Can Sorghum halepense plants be pollinized by genetically modified maize plants?***

No, they are not closely related.

***42. In a genetically modified herbicide-resistant crop, is it possible to use the associated herbicide at any time, repeatedly and at any rate?***

No, the herbicide should be applied at the right time and according to the number of times recommended for each crop cycle according to the instructions on the label.

## 5.4 Questions on non-chemical methods

***43. What methods are available for weed management that do not involve the use of herbicides?***

There are several non-chemical methods for weed control – preventative, cultural, mechanical and physical (Chapter 3.2).

***44. What are the actions of mechanical weed control methods?***

Similarly to the herbicides, the mechanical methods show different "modes of action": incorporating, pulling, breaking the vegetative organs, dragging and unearthing them (Chapter 3.2.4).

***45. Do non-chemical weed control methods have negative aspects?***

Yes, they rarely achieve an efficiency of over 80 percent; it is thus necessary to combine them to increase their effectiveness. These are not total-effect methods. One method could be effective against one species while ineffective against another. It is also important to take into account that in many cases, fuel consumption may be high.

***46. What non-chemical control methods are easily adopted by farmers?***

This will depend on the agro-ecosystem. Delay in planting, fallow and crop rotations may be effective. These methods are easily applicable. Others such as solarization, thermal weeding, plastic and organic mulching can also be applied (Table 8).

***47. How are the perennial weeds controlled without the use of herbicides?***

This is done mainly by exhausting the underground reserves of the weeds, sometimes pulling or dragging the rhizomes and tubers into the soil surface (Table 9).

***48. What criteria should be followed to design a rotation?***

Depending on the target weed, one can rotate the planting date, cycles, occupied space, crop competitive ability or harvest time (Chapter 3.2.3).

***49. What is the maximum weed stand per square metre that justifies the application of hand weeding?***

This depends on crop competitiveness, weed aggressiveness, cost of hand weeding and the likelihood of a high crop yield.

***50. What are the optimal conditions for applying mechanical control?***

The proper conditions of homogenous soil, with few stones in the field, small weeds, and sun or wind after the application of mechanical control. It is important to follow the standards of good practices (Table 12).

***51. How can the production or build-up of seeds in the soil seed bank be prevented?***

Useful operations include slashing, grazing, or hand pulling the weeds before flowering and seed setting.

***52. How can the production of rhizomes of a perennial plant be prevented or reduced?***

This can be done by weakening the plant (for example, slashing) to avoid the accumulation of nutrients in rhizomes or tubers.

***53. Are grasses susceptible to mechanical control methods?***

This depends on the species and climatic conditions. Generally, they are sensitive to burial in soil and deep ploughing, but tolerate the harrow well and may be able to regrow after slashing (Tables 8, 9 and 10).

***54. What dicot weeds are susceptible to mechanical methods?***

This depends on the species, type of soil work and environmental conditions. Cruciferae seeds are well adapted to burial in soil. Some annuals with fasciculated roots are able to survive a partial unearthing. In conclusion, the most susceptible plants are normally the annuals with fasciculated and fibrous root systems (Tables 8, 9 and 10).

***55. Is night tillage more effective than diurnal tillage?***

This depends on the target weed, but the efficacy is generally similar (Chapter 3.2.4.3).

***56. What can be expected from fire or thermal weeding?***

This is a method of total effect against annual small weeds; it does not leave any harmful residues and does not alter the soil structure. It is necessary to repeat the treatment periodically and is especially recommended for pre-emergence treatments in crops such as maize, fruit orchards, or post-emergence in onion-like crops as well in uncropped areas. It should be applied with care to avoid skin burning (Chapter 3.2.4.4).

***57. What can be expected from plastic or organic mulching?***

The plastic sheets should be opaque to light and weeding should be carried out around its holes where crops emerge. In non-degradable materials, the cost of disposal should be included in the expenses of the process. Good placement of the materials without breaking the plastic is important. Irrigation should be minimized as much as possible. Some species may proliferate under straw mulching, but most of the weeds are not able to perforate these materials (Chapters 3.2.4.5 and 3.2.4.7).

***58. Are there systems with more risks than others of generating resistance?***

Yes, all cropping systems based on the use of herbicides and not on other non-chemical control methods, e.g., crop rotation, are at risk.

***59. What is the cheapest mulching method?***

If organic materials (leaves, straw and crust) are abundant, then this should be the most economic method.

***60. How are artificial mulching methods classified from the cheapest to the most expensive ones?***

The most expensive method is the use of special paper for mulching followed by other biodegradable plastics, recycled paper, oxobiodegradable plastic, while the most economic one is polyethylene.

This is variable in each country and year, and depends on the cost of disposal or recycling non-biodegradable materials (Chapter 3.2.4.5)

***61. Can solarization be used in all cropping areas?***

No, for effective solarization, it is necessary to ensure a temperature of 40º C. for 20 consecutive days. For this reason, solarization can only be applied in areas with enough solar radiation.

***62. Can non-chemical methods cause resistance?***

No, these methods concern adaptation, which is not an inherited characteristic.

## 5.5 Questions on integrated management

***63. What are the characteristics of integrated weed management?***

Different methods are alternated to reduce the selection pressure of any control method practised. The approach should be as diverse as possible, flexible, scientifically-based, adaptable and economic (Chapter 3.3).

***64. How is it possible to combine the use of herbicides and non-chemical weed control methods?***

In cereal, both methods can be used in a crop cycle (for example, planting delay and herbicide application) or by alternating them between years, but this will depend on the crop. In vegetables, the herbicide, mulching and interrow cultivation can be applied. In orchards, slashing can be combined with herbicides or alternated between years (Chapter 3.3).

***65. Is there any "magic" procedure for weed control that can solve the problem of resistance?***

No.

***66. What is the keyword to remember in resistance management?***

Diversify.

***67. Where does resistance come from?***

It is generated in a local weed species treated with the same herbicide active ingredient or an exotic herbicide-resistant weed brought from abroad (Chapter 2).

***68. Does resistance have any positive aspects?***

It has been proven that recommendations to alternate control methods, useful for any weed management, are taken more seriously.

Yes, whenever it occurs, it is necessary to adopt other control strategies for weed management. Resistant weeds show the importance of weeds in crops, often weeds are neglected or not considered an important enough constraint to the agricultural production. This problem exists because weeds do not show spectacular effects on crops as do other pests and diseases.

***69. What is more economic, to prevent or manage resistance?***

Taking into account how difficult it is to eliminate a resistant weed in the field, prevention is the most economic way.

***70. What benefits does prevention of weed resistance to herbicides provide?***

To avoid resistance, which is very difficult to eradicate. Economically, the benefit is seen in the long term (Chapter 1.7).

***71. What are the environmental benefits of implementing an integrated weed management programme?***

Less use of herbicides due to the implementation of other non-chemical methods.

***72. Are mechanical weed control methods able to replace the use of herbicides?***

This is possible only in organic or ecological agriculture, where herbicides are not used. When applied efficiently, the herbicides are a useful and effective tool. However, it has also some disadvantages, as does any other method.

***73. What is the advantage of knowing weed species biology in managing its resistant population?***

It is essential to know the way of reproduction of the weed (vegetative or sexual), time of germination, competitiveness, seed persistence in soil and other characteristics (Tables 8 and 9).

***74. What is the role of machinery, harvesters and other implements in weed dispersal?***

They can become agents for weed spread if they move from infested fields into non-infested ones, and if the machinery is not previously cleaned.

***75. What is the role of seeds produced by a perennial weed during its cycle?***

This depends on the species. In some cases, its secondary mechanism of reproduction ensures greater dispersal and genetic recombination. Seed problems can be minimized by slashing, grazing or cutting the plant to prevent its flowering and seed dispersal.

***76. What is the role of animal excretions in weed seed dispersal?***

Many weed seeds do not decompose by passing through the animal digestive tract. Therefore, several animals spread the weed seeds, some of which have high viability. If the weeds are grazed before flowering, then this activity becomes very effective in reducing weed stands (Chapters 3.2.2 and 3.2.3).

***77. What are the effects of burning stubbles on controlling weeds? Does fire destroy seed germinative ability?***

This depends on the weed species and the fire intensity. For example, if implemented quickly, as in the case of *Lolium rigidum*, fire seems to differentiate weeds for germination the following year. In the case of *Avena*, burning stubbles may reduce its population, while for *Papaver rhoeas*, no germination reduction has been observed. It is necessary to take into account various risks derived from burning stubbles, such as the emission of $CO_2$ into the atmosphere, the loss of organic matter and hazard of fire in the field (Chapter 3.2.4.4).

***78. How can the crop reduce the weed growth and stand?***

A vigorous crop planted at the right distance and with enough water for its growth will be able to compete with weeds.

***79. Is it possible to affect the weeds before the crop establishment?***

Yes, using preventative and cultural methods (Chapter 3.2.2).

***80. Are all weed seeds destroyed when buried in soil?***

No, the species producing seeds with dormancy may remain viable for years (e.g., *Avena sterilis, Abutilon theophrasti*) (Tables 8 and 9).

***81. Can "conservation agriculture" favour the development of herbicide resistance?***

It depends. This group of technologies aims at soil preservation and other natural resources. In herbaceous crops, it is advised not to conduct mouldboard ploughing, which reduces diversification and may cause excessive use of herbicides and, subsequently, the increase of selection pressure. In woody species, it promotes the use of plant covers and may reduce this pressure.

## 5.6 Questions on weed biology

***82. Where is the resistance to spread easily, in allogamous or autogamous plants?***

It spreads easily in allogamous species (e.g., *Lolium rigidum, Papaver rhoeas*), but not in autogamous species such as *Avena* spp..

***83. Are there herbicide-resistant perennial weeds?***

Yes, an example is *Sorghum halepense* (Chapter 3.1.3).

***84. When can annual weed control favour the control of perennial weeds?***

During the initial cycle of the plant, i.e., in the seedling stage, and when the perennial herb has germinated from seeds and before it develops its vegetative organs.

***85. How is the resistance managed in annual weeds and how is it managed in perennials?***

The procedure is basically the same for both, i.e., alternating the control methods. Due to the vegetative organs in the perennials, there is a need to take special care to avoid their spreading to neighbouring fields. Once the weed is established, it is advisable to eradicate the vegetative organs or exhaust the reserves they contain (Tables 8, 9 and 10).

***86. What is the importance of the soil weed seed bank in the management of resistant populations?***

It is very important since a persistent weed seed bank of a resistant biotype may build up and provide new individuals for germination.

***87. Why is it important to prevent the production of seeds from resistant weeds? Is this applicable when managing resistant weeds?***

This is the way to avoid its seed build-up in soil and to reduce the source of new resistant individuals. Therefore, it is essential to prevent production of seeds.

***88. Can weed seeds spread from one field to another?***

The machinery for soil preparation, harvesters and irrigation canals may spread weed seeds of resistant species into new fields. In addition, the wind may also disperse some weed seeds of resistant biotypes (Table 8).

***89. What should be done to avoid the spreading of herbicide-resistant weed seeds?***

Cleaning the harvesters well prior to entering a field where no resistant biotypes are present. It is also advisable to put filters in the canals and irrigation ditches and to avoid the use of manure that is not well decomposed and that comes from areas where resistant biotypes are present.

## 5.7 Questions on technology transfer

***90. Are farmers, pesticides distributors and other agents aware of the herbicide resistance problem?***

It depends on the region, but probably the farmers should be well aware since they note when the herbicide effectiveness is reduced in the fields. Distributors should not only try to increase their sales, but to inform the farmers and advise them jointly with the agricultural extension workers.

***91. Are farmers, pesticide distributors and extension workers aware that the solution is in their hands?***

Some are, but some are completely unaware. In fact, the key point of transferring resistance technology is to raise awareness on problem-solving.

***92. What information should be transferred to farmers?***

Theoretic information and the stage of the problem in the area are important elements. In addition, information on alternative methods should also be given. The concepts to be emphasized are (Chapter 4):

- the fact that the problem of resistance is real;
- the number of registered cases of resistance and their extension;
- applicable solutions.

***93. What are the sources of information available on herbicide resistance?***

There are materials in different languages in various websites, several publications and leaflets that clearly explain the problem of resistance. The website www.weedscience.com cites most information on the issue. It is also useful to deliver lectures in the affected areas to explain the problem, and to provide scientific information and to indicate the available books and publications, some of which are cited in the bibliography here, and sources available in the Internet (Chapter 4.1).

**94. What are the methods used for disseminating information on herbicide resistance?**

They can be grouped in virtual (online) and non-virtual. Non-virtual implies field visits with the farmers in the area, organization of field days and working group sessions. By using the Internet, it is possible to consult websites with information related to resistance from academic institutions and from the agrochemical industry producing herbicides.

**95. What should the content be of a field visit or a one- or two-day workshop?**

A field visit should show the reality of the cases of resistance, its presence in the field and possible fields where the resistance has been solved. This enables the participants to see the problem *in situ* and the possibility of solving it.

In addition to the above information, in a one- or two-day workshop, it is possible to go deeply into theoretical concepts of resistance, to familiarize the participants with the experience of experts on the subject and exchange information among the farmers and technicians affected by this problem. As in any informative activity, dialogue should be promoted as much as possible.

**96. What method is more effective for information transfer, virtual or non-virtual methods?**

The best method is the one involving more participation and information for those affected by resistance. It will also depend on the availability of some equipment and Internet connection in accessing information in a quick and pleasant manner. Visits to fields affected by resistance are advisable for those who have never have exposed to such problems.

**97. Do extension workers and farmers need to receive information on herbicide resistance?**

Obviously, they are the main actors in their fields.

### *98. What information can be obtained from websites dealing with herbicide resistance?*

It is possible to learn about confirmed cases of resistance for a particular weed species and a particular herbicide in any country. It is also possible to read the details of a complete study in each case. Other information may include ways to detect resistance, how to manage resistant populations and specific information on each weed.

### *99. Is it ethical to sell a herbicide for its use in a field where its resistance is already present?*

No, it is not ethical. Just as when the physician asks the patient whether he or she is allergic to one or another medication before prescribing it, the seller should also ask about the history of the field to be treated and to see whether the herbicide has any possibility to control the weeds in the infested field.

### *100. Who should be responsible for the problems of herbicide resistance?*

All participants in weed management activities, including those applying the herbicides, chemicals retailers and the extension workers. Suitable actions of these stakeholders may contribute to prevent the resistance or at least to detect it early.

### *101. How is possible to promote the use of herbicides in areas where they have not been used?*

This can be done based on good knowledge of the available herbicides and how to apply them correctly. Experiences on the application of these chemicals from other areas are also valuable.

Herbicides are good tools for effective weeding. The use of these chemicals enables farmers to save the labour of three or four hand weedings in any annual or perennial crop. Herbicide application has also enabled farmers to grow major food and industrial crops, such as rice, wheat, maize, fruits, sugar cane and some others in large areas in several countries of the world. However, the prolonged use of the same herbicide can cause problems of herbicide resistance, a phenomenon consisting of the selection of the resistant population of a weed previously fairly well controlled by the same herbicide. In the last three decades, the number of cases of herbicide-resistant weeds has increased considerably worldwide. The biotypes of resistant weeds become a more serious problem than the weed itself, since they are pests of increased hazard due to the difficulty in eliminating them. The best resistance management is through prevention, using economically and technically effective strategies. Effective prevention is one that is able to reduce the problems of selection pressure. This material has been prepared by a group of authors from Spain, who are involved in studies and actions on resistance prevention and management. This important contribution should serve as guidance on herbicide resistance prevention for agricultural extension workers. The material carefully describes the activities to be carried out by personnel working with farmers and the strategies to implement for preventing and managing resistance. The application of these lessons may help towards a better use of herbicides in general and the avoidance of resistance.

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